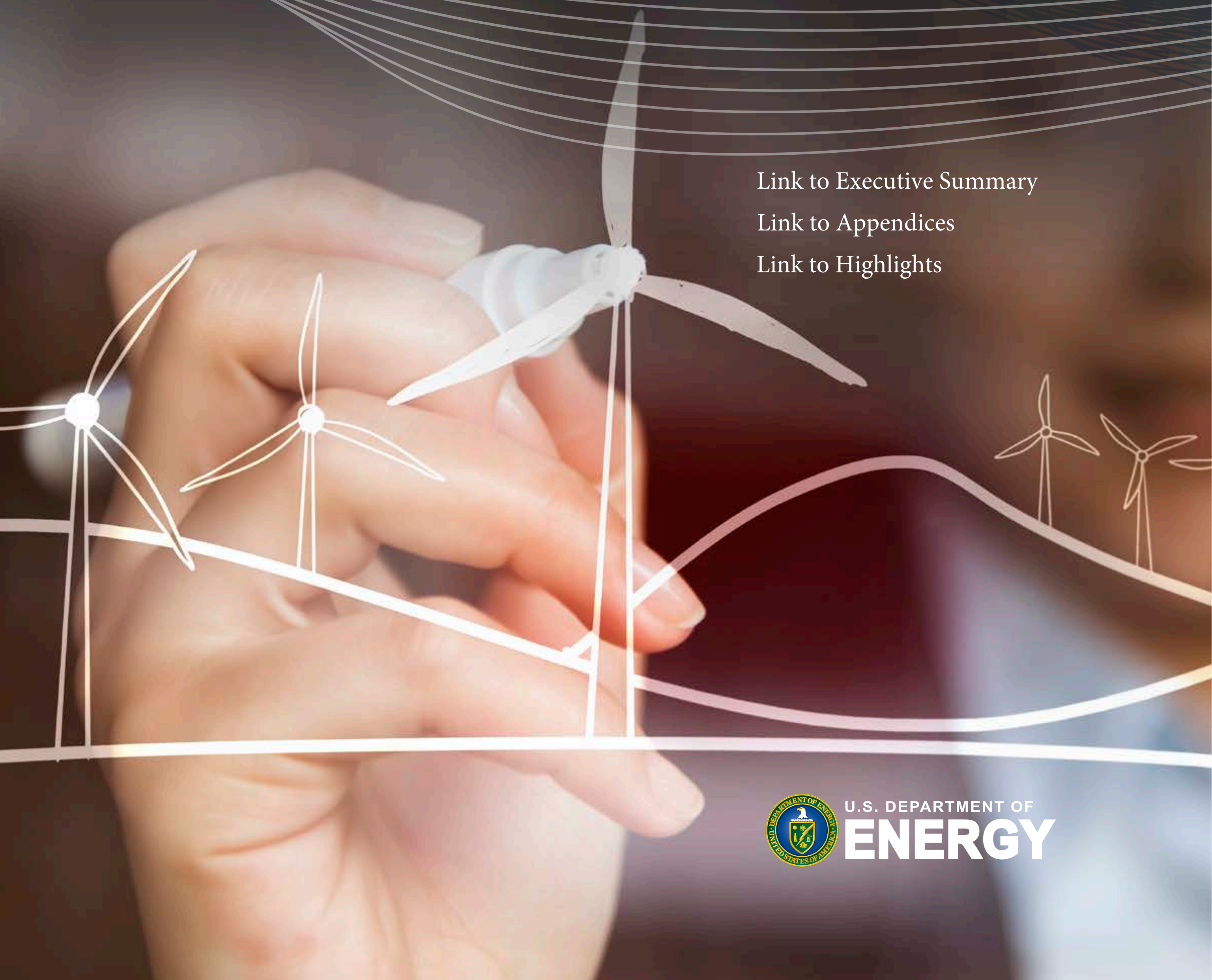
Wind Vision:

A New Era for Wind Power in the United States



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Message from the Director

The wind industry can be characterized by the substantial growth of domestic manufacturing and the level of wind deployment seen in recent years. Wind power systems are now seen as a viable and competitive source of electricity across the nation. Wind power's emerging role is an important option in a portfolio of new energy solutions for future generations. More than 4.5% of our nation's electricity came from wind power in 2013, placing the industry at a crossroads between the opportunities of higher energy penetration and the challenges of increased competition, policy uncertainty, access to transmission and lower energy demand.

The primary goal of the *Wind Vision* was to gain insights, after analyzing and quantifying a future scenario for wind energy, that consider our domestic manufacturing capacity, current and projected cost trends, sensitivities to future demand and fuel prices, and transmission needs. The *Wind Vision* was accomplished by bringing together leaders in energy in an effort to pool their insights, build upon their advancements, and learn from their accomplishments to project a credible future supported by the economic and societal benefits of wind energy.

In writing the *Wind Vision*, we recognize that the Energy Department is not the sole agent to drive a new future for the industry, but the federal Wind Program can provide focus and direction by leading efforts to accelerate the development of next-generation wind power technologies and assisting in solving key market challenges.

I would like to express my deepest sense of gratitude to the hundreds of individuals across our agency, industry, academia, and our national labs for their support, feedback and strategic interest in a renewed vision for wind energy. Their level of involvement signals a bright future for the wind industry.

The stakes for the nation are high. I am confident that, with sustained leadership in innovation, U.S. wind power will continue to make a significant contribution to the ever-evolving energy landscape. The *Wind Vision* is intended to assist in prioritizing the decisions needed to increase the economic competitiveness of the U.S. wind industry throughout the 21st century.

José Zayas
Director, Wind and Water Power Technologies Office
U.S. Department of Energy
March 12, 2015

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Acronyms

AC	alternating current
AEO	*Annual Energy Outlook*
AP2 (formerly APEEP)	Air Pollution Emission Experiments and Policy
AWEA	American Wind Energy Association
AWC	Atlantic Wind Connection
AWST	AWS Truepower
AWWI	American Wind Wildlife Institute
BA(s)	balancing area(s)
BAU	Business as Usual or Business-as-Usual
BLM	Bureau of Land Management
BMP(s)	best management practice(s)
BOEM	Bureau of Ocean Energy Management
BPT	benefit per ton
Btu	British thermal unit
CAPEX	capital expenditures
CBO	Congressional Budget Office
CCS	carbon capture and sequestration (or storage)
CF	capacity factor
CO_2	carbon dioxide
CREZ	Competitive Renewable Energy Zone

CRS	Congressional Research Service
CSAPR	Cross-State Air Pollution Rule
CSP	concentrating solar power
DC	direct current
DMME	Department of Minerals, Mines, and Energy (Virginia)
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DWEA	Distributed Wind Energy Association
EIA	U.S. Energy Information Administration
EIPC	Eastern Interconnection Planning Collaborative
ELI	Environmental Law Institute
EPA	U.S. Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
ESA	Endangered Species Act
FAA	Federal Aviation Administration
FAU	Florida Atlantic University
FCR	fixed charge rate
FERC	Federal Energy Regulatory Commission
ft	feet
FTE	full-time equivalent (jobs)

GAO	U.S. Government Accountability Office
GCC	grid connection cost
GCF	gross capacity factor
GHG	greenhouse gas
GW	gigawatt(s)
GWEC	Global Wind Energy Council
HCl	hydrogen chloride
HCP	Habitat Conservation Plan
HUC	Hydraulic Unit Code
HVDC	high-voltage direct-current
HVAC	high-voltage alternating current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGCC	integrated gasification combined cycle
I-O	input-output
IP	Interim Policy
ISO	independent system operator
ITC	investment tax credit
IVGTF	Integration of Variable Generation Task Force (of NERC)
IWG	Interagency Working Group (on Social Cost of Carbon)

JEDI	Jobs and Economic Development Impacts (model)
K	kindergarten
kg	kilogram(s)
km	kilometer(s)
kV	kilovolt(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
lb	pound(s)
LBNL	Lawrence Berkeley National Laboratory
LCA	life-cycle assessment
LCOE	levelized cost of electricity
LWST	Low wind speed technology
MassCEC	Massachusetts Clean Energy Center
Metocean	meteorological and oceanographic
m	meter(s)
m/s	meters per second
MACRS	modified accelerated cost recovery system
MATS	Mercury and Air Toxics Standards
MBTA	Migratory Bird Treaty Act
MMBtu	million British thermal unit
MISO	Midcontinent Independent System Operator

MW	megawatt(s)
MWh	megawatt-hour
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation
NGCC	natural gas–combined cycle
NGCCS	natural gas with carbon capture and storage
NGCT	natural gas-fired combustion turbine
NGO(s)	non-governmental organization(s)
NOAA	National Oceanic and Atmospheric Administration
NO_X	nitrogen oxides
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center
O&M	operations and maintenance
OCC	overnight capital cost
OCS	outer continental shelf
OEM	original equipment manufacturer
OPEX	operating expenses (or expenditures)
ORNL	Oak Ridge National Laboratory
OSW	offshore wind
PM	particulate matter (PM_{10} and $PM_{2.5}$)

PPA	power purchase agreement
PTC	production tax credit
PV	photovoltaic
R&D	research and development
REC(s)	renewable energy credit(s)
ReEDS	Regional Energy Deployment System (model)
RIA	Regulatory Impact Analysis
RPM	revolutions per minute
RPS	renewable portfolio standard
RTO(s)	regional transmission organization(s)
SAIC	Science Applications International Corporation
SCC	social cost of carbon
SO_2	sulfur dioxide
SolarDS	Solar Deployment System (model)
STEM	science, technology, engineering, and math
SWiFT	Scaled Wind Farm Technology
t	metric tonne
TES	thermal energy storage
TRG(s)	techno-resource group(s)
TSS	Traffic Separation Schemes
TWh	terawatt-hour(s); trillion kWh

UK	United Kingdom
UNEP	United Nations Environment Program
U.S.C.	United States Code
USCG	U.S. Coast Guard
USFWS	U.S. Fish and Wildlife Service
UVIG	Utility Variable-Generation Integration Group
WAC	watts alternating current
WDC	watts direct current
WACC	weighted average cost of capital
WEA	wind energy area (offshore)
WinDS	Wind Deployment System (now ReEDS)
WV	*Wind Vision*
WWPTO	Wind and Water Power Technologies Office (DOE)

Executive Summary: Overview

The U.S. Department of Energy's (DOE's) Wind and Water Power Technologies Office led a comprehensive analysis to evaluate future pathways for the wind industry. Through a broad-based collaborative effort, the *Wind Vision* had four principal objectives:

1. Documentation of the current state of wind power in the United States and identification of key technological accomplishments and societal benefits over the decade leading up to 2014;
2. Exploration of the potential pathways for wind power to contribute to the future electricity needs of the nation, including objectives such as reduced carbon emissions, improved air quality, and reduced water use;
3. Quantification of costs, benefits, and other impacts associated with continued deployment and growth of U.S. wind power; and
4. Identification of actions and future achievements that could support continued growth in the use and application of wind-generated electricity.

The conclusions of this collaborative effort, summarized below, demonstrate the important role that wind power has in the U.S. power sector and highlight its potential to continue to provide clean, reliable and affordable electricity to consumers for decades to come. The *Wind Vision* study does not evaluate nor recommend policy actions, but analyzes feasibility, costs, and benefits of increased wind power deployment to inform policy decisions at the federal, state, tribal, and local levels.

A High U.S. Wind Penetration Future is Achievable, Affordable and Beneficial

Wind power is one of the fastest-growing sources of new electricity capacity and the largest source of new renewable power generation added in the United States since 2000. Changes in wind power market dynamics, costs, technology, and deployment since the 2008 DOE report, *20% Wind Energy by 2030,* are documented through analysis of recent history, current status (as of 2013), and projected trends. The analysis of wind installation and operational experience as of 2013 concludes that:

- Wind deployment, including associated manufacturing and installation activities, has demonstrated the ability to scale to satisfy rapid build demands, including the deployment levels of the *Wind Vision Study Scenario* described below;
- Wind generation variability has a minimal and manageable impact on grid reliability and related costs; and
- Environmental and competing use challenges for local communities, including land use, wildlife concerns, and radar interference issues, can be effectively managed with appropriate planning, technology, and communication among stakeholders.

Deployment of wind technology for U.S. electricity generation provides a domestic, sustainable, and essentially zero-carbon, zero-pollution and zero-water use U.S. electricity resource.

The *Wind Vision* report deepens the understanding of U.S. wind power's potential contributions to clean, reliable electricity generation and related economic and other societal benefits. Results are provided from analyses of U.S. greenhouse gas (GHG) and pollution reductions, electricity price impacts, job and manufacturing trends, and water and land use impacts—for the years 2020, 2030, and 2050. A high U.S. wind penetration is achievable but will require actions as identified in the *Wind Vision* Roadmap.

Study Summary

The *Wind Vision* report results from a collaboration of the DOE with over 250 experts from industry, electric power system operators, environmental stewardship organizations, state and federal governmental agencies, research institutions and laboratories, and siting and permitting stakeholder groups. The *Wind Vision* report updates and expands upon the DOE's 2008 report, *20% Wind Energy by 2030,* through analysis of scenarios of wind power supplying 10% of national end-use electricity demand by 2020, 20% by 2030, and 35% by 2050. This *Study Scenario* provides a framework for conducting detailed quantitative impact analyses. The *Wind Vision* analysis concludes that it is both viable and economically compelling to deploy U.S. wind power generation in a portfolio of domestic, low-carbon, low-pollutant power generation solutions at the *Study Scenario* levels. Realizing these levels of deployment, however, would depend upon both immediate and long-term actions—principally identifying continued wind cost reductions, adding needed transmission capacity, and supporting and enhancing siting and permitting activities—to complement any federal, state, tribal, and local policies that may be enacted. Described in the *Wind Vision* Roadmap, these actions focus on specific key challenges and stakeholder actions that should be considered.

Analysis Overview

The *Wind Vision* analysis models three core scenarios in order to better understand the sensitivities in deployment to various external drivers and, subsequently, to understand the likely economic and environmental effects of those drivers on the scenarios; a *Baseline Scenario*, with U.S. wind capacity held constant at 2013 levels of 61 gigawatts (GW); a *Business-as-Usual Scenario* (*BAU*), and a *Study Scenario*. The *BAU Scenario* is used to evaluate the industry's domestic economic competitiveness today and into the future based on central expectations of future fossil fuel and renewable costs, energy demand, scheduled existing fleet retirements, and federal and state policies enacted as of January 1, 2014.

The *Study Scenario* starts with current manufacturing capacity (estimated at 8-10 GW of nacelle assembly and other large turbine components within the U.S. today) and applies central projections for variables such as wind power costs, fossil fuel costs, and energy demand in order to arrive at a credible projected pathway that would maintain the existing industry, for purposes of calculating potential social and economic benefits. The *Study Scenario* is a plausible outcome, representing what could come about through a variety of pathways, including aggressive wind cost reductions, high fossil fuel costs, federal or state policy support, high demand growth, or different combinations of these factors. The resulting *Study Scenario*—10% by 2020, 20% by 2030, and 35% by 2050 wind energy as a share of national end-use electricity demand—is compared against the *Baseline Scenario* to estimate costs, benefits, and other impacts associated with potential future wind deployment.

National average wind costs are rapidly approaching cost competitive levels, but, without incentives, these costs are higher than the national average for natural gas and coal costs as of 2013. With continued cost reductions, the *Wind Vision* analysis envisions new wind power generation costs to be below national average costs for both new and existing fossil plants within the next decade.

The *Wind Vision* study concludes that with continued investments in technology innovation, coupled with a transmission system that can provide access to high resource sites and facilitate grid integration reliably and cost-effectively, the *Study Scenario* is an ambitious yet viable deployment scenario. Further, the analysis concluded that the U.S. wind supply chain has capacity to support *Study Scenario* wind deployment levels, with cumulative installations of 113 GW of generating capacity by 2020, 224 GW by 2030, and 404 GW by 2050, building from 61 GW installed as of the end of 2013.

Results: Overall Positive Benefit to the Nation

The *Wind Vision* concludes that U.S. wind deployment at the *Study Scenario* levels would have an overall positive economic benefit for the nation. Numerous economic outcomes and societal benefits for the *Study Scenario* were quantified, including:*

- An approximately 1% increase in electricity costs through 2030, shifting to long-term cost savings of 2% by 2050. This results in cumulative system cost savings of $149 billion by 2050.
- Cumulative benefits of $400 billion (net present value 2013-2050) in avoided global damage from GHGs with 12.3 gigatonnes of avoided GHG emissions through 2050. Monetized GHG benefits exceed the associated costs of the *Study Scenario* in 2020, 2030, and 2050 and on a cumulative basis are equivalent to a levelized global benefit from wind energy of 3.2¢/kWh of wind.
- Cumulative benefits of $108 billion through 2050 for avoided emissions of fine particulate matter (PM), nitrogen oxides (NO_x), and sulfur dioxides (SO_2). Monetized criteria air pollutant benefits exceed the associated costs of the *Study Scenario*

*Quantitative results presented in this Overview are based on the *Central Study Scenario*, defined on Page xxviii. Modeling analysis is based on current (as of 2013) and projected trend data to inform inputs, assumptions, and other constraints. Financial results are reported in 2013$ except where otherwise noted.

in 2020, 2030, and 2050, and on a cumulative basis are equivalent to a levelized public health benefit from wind energy of 0.9¢/kWh of wind.

- Quantified consumer cost savings of $280 billion through 2050 from reduced natural gas prices outside of the electricity sector, in response to reduced demand for natural gas and its price elasticity. This is equivalent to a levelized consumer benefit from wind energy of 2.3¢/kWh of wind.
- A 23% reduction in water consumed by the electric sector in 2050, with significant value in locations with constrained water availability.
- Transmission capacity expansion similar to recent national transmission installation levels of 870 miles per year, assuming equivalent single-circuit 345-kilovolt lines with a 900-MW carrying capacity.
- Land use requirements for turbines, roads, and other wind plant infrastructure of 0.04% of contiguous U.S. land area in 2050.

The *Study Scenario* also identifies certain other impacts, such as those to wildlife and local communities. It does not, however, monetize these impacts, which are highly dependent on specific locational factors.

Roadmap for Key Stakeholder Actions

The *Wind Vision* analysis concludes that, while the *Study Scenario* is technically viable and economically attractive over the long run, a number of stakeholder actions should be considered to achieve the associated wind deployment levels. Improving wind's competitive position in the market can help the nation maintain its existing wind manufacturing infrastructure and the wide range of public benefits detailed in the *Wind Vision*, including reducing carbon emissions. The *Wind Vision report* outlines a roadmap for moving forward and identifies the following key activities, developed collaboratively with industry and stakeholders:

- Reducing wind power costs;
- Expanding the developable areas for wind power; and
- Deploying wind in ways that increase economic value for the nation, including support for U.S. jobs and U.S. manufacturing.

Wind cost reductions do not depend on disruptive technological breakthroughs, but do rely on continued cost improvements, including rotor scale-up; taller towers to access higher wind speeds; overall plant efficiency improvements achieved through advanced controls; improved plant designs enabled by deepened understanding of atmospheric physics; installation of both intra-region and inter-region transmission capacity to high quality wind resource locations; and collaboration and co-existence strategies for local communities and wildlife that support the timely and cost-effective installation of wind power plants.

Risk of Inaction

Wind's growth over the decade leading to 2014 has been driven largely by wind technology cost reductions and federal and state policy support. Without actions to support wind's competitive position in the market going forward, the nation risks losing its existing wind manufacturing infrastructure and much of the public benefit illustrated by the *Wind Vision* analysis.

Conclusions

The *Wind Vision* analysis demonstrates the economic value that wind power can bring to the nation, a value exceeding the costs of deployment. Wind's environmental benefits can address key societal challenges such as climate change, air quality and public health, and water scarcity. Wind deployment can provide U.S. jobs, U.S. manufacturing, and lease and tax revenues in local communities to strengthen and support a transition of the nation's electricity sector towards a low-carbon U.S. economy. The path needed to achieve 10% wind by 2020, 20% by 2030, and 35% by 2050 requires new tools, priorities, and emphases beyond those forged by the wind industry in growing to 4.5% of current U.S. electricity demand. Consideration of new strategies and updated priorities as identified in the *Wind Vision* could provide substantial positive outcomes for future generations.

The *Study Scenario* results in cumulative savings, benefits, and an array of additional impacts by 2050.

System Costs[a]	Benefits[b,c]		
$	GHG	Air Pollution	H_2O
$149 billion (3%) lower cumulative electric sector expenditures	14% reduction in cumulative GHG emissions (12.3 gigatonnes CO_2-equivalents), saving $400 billion in avoided global damages	$108 billion savings in avoided mortality, morbidity, and economic damages from cumulative reductions in emissions of SO_2, NO_X, and PM 21,700 premature deaths from air pollution avoided	23% less water consumption and 15% less water withdrawals for the electric power sector

Additional Impacts

Energy Diversity	Jobs	Local Revenues	Land Use	Public Acceptance and Wildlife
Increased wind power adds fuel diversity, making the overall electric sector 20% less sensitive to changes in fossil fuel costs. The predictable, long-term costs of wind power create downward price pressure on fossil fuels that can cumulatively save consumers $280 billion from lower natural gas prices outside the electric sector.	Approximately 600,000 wind-related gross jobs spread across the nation.	$1 billion in annual land lease payments $440 million annual lease payments for offshore wind plants More than $3 billion in annual property tax payments	Less than 1.5% (106,000 km^2) of contiguous U.S. land area occupied by wind power plants Less than 0.04% (3,300 km^2) of contiguous U.S. land area impacted by turbine pads, roads, and other associated infrastructure	Careful siting, continued research, thoughtful public engagement, and an emphasis on optimizing coexistence can support continued responsible deployment that minimizes or eliminates negative impacts to wildlife and local communities

Note: Cumulative costs and benefits are reported on a Net Present Value basis for the period of 2013 through 2050 and reflect the difference in impacts between the *Central Study Scenario* and the *Baseline Scenario*. Results reported here reflect central estimates within a range; see Chapter 3 for additional detail. Financial results are reported in 2013$ except where otherwise noted.

a. Electric sector expenditures include capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled, but excludes consideration of estimated benefits (e.g., GHG emissions).

b. Morbidity is the incidence of disease or rate of sickness in a population.

c. Water consumption refers to water that is used and not returned to the source. Water withdrawals are eventually returned to the water source.

Executive Summary: Key Chapter Findings

ES.1 Introduction

Wind power is one of the fastest-growing sources of new electricity supply and the largest source of new renewable power generation added in the United States since 2000. Wind power generation in the United States has tripled, increasing from 1.5% of annual electricity end-use demand in 2008 to 4.5% through 2013. As of 2013, there were more than 61 gigawatts (GW) of wind generating capacity installed, and electric system operators and utilities throughout the country routinely consider wind power as part of a diverse electricity generation portfolio. Interest in wind power is stimulated by its abundant resource potential (more than 10 times current electricity demand); competitive, long-term stable pricing; economic development potential; and environmental attributes, including its ability to support reduced carbon emissions, improved air quality, and reduced water use.

At the same time, low natural gas prices, low wholesale electricity prices, and reduced demand for electricity since 2008 are impacting investments for all new electric generation. Annual U.S. wind capacity additions have varied dramatically as a function of these factors as well as trends in wind power costs and policy.

In this context, DOE initiated the *Wind Vision* analysis. Led by the Wind and Water Power Technologies Office in DOE's Office of Energy Efficiency and Renewable Energy, the collaboration that resulted in the *Wind Vision* represents more than 250 energy experts with an array of specialties and includes grid operators, the wind industry, science-based organizations, academia, governmental agencies, and environmental stewardship organizations. The *Wind Vision* serves as an update and significant expansion of an earlier DOE report, *20% Wind Energy by 2030.*[1]

At its core, the *Wind Vision* is intended to inform a broad set of stakeholders—including the industry, policymakers, and the public—on the implications of continued U.S. wind deployment. The analysis conducted does not result in a prediction or forecast of the future, but instead assesses the incremental costs associated with the deployment of wind power as a major part of the nation's energy future, and compares these costs to the value of the resulting benefits. One of the greatest challenges for the 21st century will be bringing affordable, secure, clean energy to the world. This report considers the contribution of U.S. wind power in resolving that challenge.

ES.1.1 Project Perspective and Approach

In 2008, DOE evaluated the technical feasibility of a scenario in which 20% of the nation's annual electricity consumption was served by wind power in 2030. The resulting report, *20% Wind Energy by 2030,* concluded that the U.S. power system could support a 20% wind penetration scenario with an increase in electric sector expenditures of 2% over the time frame of the study (2008–2030), relative to a future with no new wind. The report also identified key activities to be addressed, including expanding transmission infrastructure, reducing the cost of wind power, integrating wind reliably into the bulk power system, and addressing potential concerns related to siting and permitting of wind plants. Since the release of *20% Wind Energy by 2030,* wind power's installed capacity has increased by a factor of three. As of 2013, annual installations have surpassed the initial levels envisioned in the 20% scenario and progress has been made across the challenges that were identified. The *Wind Vision* documents the industry's progress since the 2008 report, leveraging the past to inform future opportunities.

1. *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply.* U.S. Department of Energy. Washington, DC: DOE, 2008. Accessed Feb. 4, 2015: *http://energy.gov/eere/wind/20-wind-energy-2030-increasing-wind-energys-contribution-us-electricity-supply*.

Analytical Framework of the *Wind Vision*	
Wind Vision Study Scenario	The *Wind Vision Study Scenario,* or *Study Scenario*, applies a trajectory of 10% of the nation's end-use demand served by wind by 2020, 20% by 2030, and 35% by 2050. It is the primary analysis scenario for which costs, benefits, and other impacts are assessed. The *Study Scenario* comprises a range of cases spanning plausible variations from central values of wind power and fossil fuel costs. The specific *Study Scenario* case based on those central values is called the *Central Study Scenario*.
Baseline Scenario	The *Baseline Scenario* applies a constraint of no additional wind capacity after 2013 (wind capacity fixed at 61 GW through 2050). It is the primary reference case to support comparisons of costs, benefits, and other impacts against the *Study Scenario*.
Business-as-Usual Scenario	The *Business-as-Usual (BAU) Scenario* does not prescribe a wind future trajectory, but instead models wind deployment under policy conditions current on January 1, 2014. The *BAU Scenario* uses demand and cost inputs from the Energy Information Administration's *Annual Energy Outlook 2014*.

Note: Percentages characterize wind's contribution to the electric sector as a share of end-use electricity demand (net wind generation divided by consumer electricity demand).

The *Wind Vision* analysis also seeks to provide better understanding of the future potential of wind power and quantify the costs and benefits of continued investment in wind power. The analysis, modeling inputs, and conclusions presented are based on the best available information from the fields of science, technology, economics, finance, and engineering, and include the historical experience gained from industry growth and maturation in the decade leading up to 2014.

Finally, the *Wind Vision* is action-oriented. It examines the continued development and use of wind power in the United States. The *Wind Vision* roadmap identifies key challenges and the means by which they might be resolved. Priorities aim at positioning wind power to support the continued transformation of the nation's electric power sector.

Although policy is a key variable that is expected to impact the future of wind power in the United States, no policy recommendations are included in the *Wind Vision.* Such recommendations are outside the scope of the current effort. Nonetheless, the *Wind Vision,* and in particular the assessment of costs and benefits, is intended to facilitate informed discussions among diverse stakeholder groups regarding the future of wind power within the electric power sector of the United States. Points of emphasis in the *Wind Vision* analysis are divided into three discrete time-scales: near-term (2020), mid-term (2030), and long-term (2050).

The primary analysis of the *Wind Vision* centers on a future scenario in which wind energy serves 10% of the nation's end-use demand by 2020, 20% by 2030, and 35% by 2050. This scenario, called the *Wind Vision Study Scenario,* was identified as an ambitious but credible scenario after conducting a series of exploratory scenario modeling runs under *Business-as-Usual* conditions. In order to quantify the costs, benefits, and other impacts of future wind deployment, the outcomes of the *Study Scenario* are compared against those of a reference *Baseline Scenario* that fixes installed wind capacity at year-end 2013 levels of 61 GW. The *Baseline Scenario* and *Study Scenario* are not goals or future projections of wind power. Rather they comprise an analytical framework that supports detailed analysis of potential costs, benefits, and other impacts associated with future wind deployment. These three scenarios—*Study Scenario, Baseline Scenario, and Business-as-Usual Scenario*—are summarized above and constitute the primary analytical framework of the *Wind Vision.*

The *Wind Vision* analysis conducts an assessment of future wind power growth projections using a "Business-as-Usual" framework and sensitivities on key variables such as wind power costs, fossil fuel prices, and electricity demand to understand the opportunities for wind (presented in Chapter 1 of the *Wind Vision* report). This evaluation assists in identifying a credible scenario for further analysis of costs and benefits and in highlighting specific future actions that could support continued wind growth, including continued cost reductions.

ES.1.2 Understanding the Future Potential for Wind Power

In order to structure a model to consider the future potential for wind power, the *Wind Vision* starts with *Business-as-Usual,* or *BAU*, conditions. Analysis was performed using the National Renewable Energy Laboratory's Regional Energy Deployment System[2] (ReEDS) capacity expansion model and other supporting models and analyses. The ReEDS model relies on system-wide least-cost optimization to estimate the type and location of fossil, nuclear, renewable, and storage resource development; the transmission infrastructure expansion requirements of those installations; and the generator dispatch and fuel needed

Table ES.1-1. Modeling Inputs and Assumptions in *Business-as-Usual Scenario* Modeling[3,4,5]

Modeling Variables	*Business-as-Usual (BAU) Scenario*	Sensitivity Variables
Electricity demand	AEO 2014 Reference Case (annual electric demand growth rate 0.7%)	1: AEO 2014 High Economic Growth Case (annual electric demand growth rate 1.5%) 2: AEO 2014 Low Economic Growth Case (annual electric demand growth rate 0.5%)
Fossil fuel prices	AEO 2014 Reference Case	1: Low Oil and Gas Resource and High Coal Cost cases (AEO 2014) 2: High Oil and Gas Resource and Low Coal Cost cases (AEO 2014)
Fossil technology and nuclear power costs	AEO 2014 Reference Case	None
Wind power costs	Median 2013 costs, with cost reductions in future years derived from literature review	1: Low costs: median 2013 costs and maximum annual cost reductions reported in literature 2: High costs: constant wind costs from 2014–2050
Other renewable power costs	Literature-based central 2013 estimate and future cost characterization	None
Policy	Policies as current and legislated on January 1, 2014	None
Transmission expansion	Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative	None

2. The Regional Energy Deployment System (ReEDS) is a long-term capacity-expansion model for the deployment of electric power generation technologies and transmission infrastructure throughout the contiguous United States. ReEDS is designed to analyze critical issues in the electric sector, especially with respect to potential energy policies, such as clean energy and renewable energy standards or carbon restrictions. See *http://www.nrel.gov/analysis/reeds/* for more information.

3. *Annual Energy Outlook 2014.* DOE/EIA-0383(2014). Washington, DC: U.S. Department of Energy, Energy Information Administration, 2014. Accessed Dec. 14, 2014: *http://www.eia.gov/forecasts/aeo/*.

4. *Phase 2 Report: DOE Draft—Parts 2–7, Interregional Transmission Development and Analysis for Three Stakeholder Selected Scenarios.* Work performed by Eastern Interconnect Planning Collaboration under contract DE-OE0000343. Washington, DC: U.S. Department of Energy, December 2012. Accessed Feb. 4, 2015: *http://www.eipconline.com/Phase_II_Documents.html*.

5. *Electric Power Monthly.* U.S. Department of Energy, Energy Information Administration, 2014. Accessed Dec. 14, 2014: *www.eia.gov/electricity/monthly/*.

to satisfy regional demand requirements and maintain grid system adequacy. The model also considers technology, resource, and policy constraints.

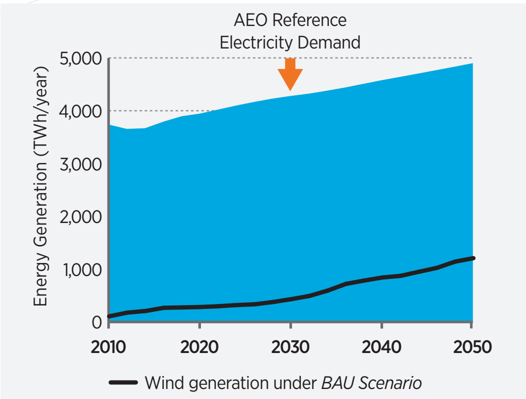
***BAU* conditions assume a future scenario under enacted federal and state policies as of January 1, 2014. Modeling inputs were extracted from the published literature as well as the DOE Energy Information Administration's Annual Energy Outlook (AEO) 2014.** Literature sources were used to develop future projections of renewable power cost and performance. The AEO was the source for fossil and nuclear technology cost and performance projections, as well as the source for fuel prices and electricity load growth projections. The sources of modeling inputs are summarized in Table ES.1-1.

***BAU* conditions indicate that growth in wind generation and capacity will be limited through 2030 (Figure ES.1-1), with more robust growth occurring between 2030 and 2050.** Wind generation is projected to settle at about 7% of total electricity demand in 2016 after projects currently under construction (and qualifying for the federal production tax credit) are placed into service. *BAU* modeling projects minimal further growth to 10% by 2030. For the period 2015–2030, average annual new capacity additions are estimated at 3 GW/year, substantially below recent (as of 2013) capacity additions. Negative impacts to the wind industry manufacturing sector and employment would be expected under *BAU.* After 2030, however, wind becomes more competitive as a result of continued cost improvements, projected increases in fossil fuel prices, and increased demand for new power generation. As a share of total U.S. electricity demand, wind power reaches 25% in 2050 under the *BAU Scenario,* with average annual new capacity additions from 2031 to 2050 corresponding generally to historical levels of capacity additions between 2009 and 2013.

Analysis results are informed by an array of sensitivities with market conditions that are unfavorable to wind. These conditions were developed to understand wind growth assuming no further cost reductions, AEO 2014 low coal and natural gas prices, and AEO 2014 low electricity demand growth. An array of factors could shift growth in wind capacity and generation even later in the study period (e.g., after 2040), such as continued low fossil fuel prices and no further reductions in wind power costs.

Other factors and market conditions, however, such as low wind power costs, high fossil fuel prices, or high electricity demand can accelerate future wind growth and drive wind penetration (as a share of total U.S. electricity demand) (Figure ES.1-2). In combination, low wind power costs and high fossil fuel prices support wind generation levels approaching 10% by 2020, 25% by 2030, and 40% by 2050.

Under *BAU Scenario* conditions, wind stagnates and annual installations fall to levels 50% or more below the latest five-year average.



Historical and Average New Wind Capacity Additions Under *BAU Scenario*

Period	GW/year	% End-Use Electricity Demand
2009–2013 (actual)	7	4.5%
2014–2020	4	7%
2021–2030	3	10%
2031–2050	8	25%

Note: The *BAU Scenario* assumes AEO Reference Case fuel costs, AEO Reference Case electricity demand, median values for renewable energy costs derived from literature, and policy as current and legislated on January 1, 2014. Percentage of end-use electricity demand data are contributions as of the end of the indicated period (e.g., 2009–2013).

Figure ES.1-1. Wind generation and average new capacity additions under *BAU*

The *Study Scenario* falls within the range of economic sensitivities on the *BAU Scenario.*

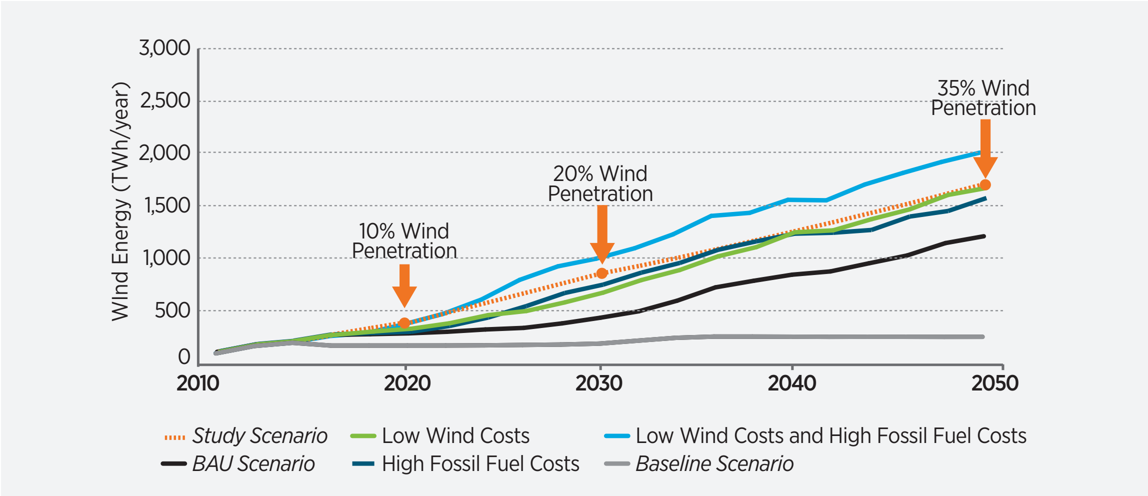


Figure ES.1-2. *Wind Vision Study Scenario* relative to *BAU* and sensitivities[6]

Analysis results are informed by an array of sensitivities with conditions that are favorable to wind. These conditions were developed to understand wind growth assuming aggressive wind cost reductions, AEO 2014 high coal and natural gas prices, and AEO 2014 high demand growth (Figure ES.1-2). When imposed independently, changes in these variables support levels of new wind capacity additions that are comparable to recent historical levels (e.g., 7 GW/year from 2009 to 2013) in the near-term (2020) and in excess of historical levels from 2030 to 2050. In combination, these variables can support levels of new wind growth on the order of 10–15 GW/year throughout the period of analysis.

At the core of the *Wind Vision* analysis is an assessment of costs, benefits, and other impacts from continued wind deployment. Evaluation of costs and benefits requires the development of a future scenario, identified as the *Wind Vision Study Scenario* (or *Study Scenario*), and a reference case, identified as the *Baseline Scenario.* The *Study Scenario* is grounded in the range of credible scenarios examined in the *BAU* and related sensitivity analyses, with specific bounds based on aggressive wind power cost reduction, high fossil fuel prices, or a combination of both. This approach illuminates key opportunities and challenges associated with continued wind power growth, and compares them against an array of environmental and other benefits associated with the scenarios.

ES.1.3 Defining a Credible Scenario to Calculate Costs, Benefits, and Other Impacts

Drawing from the analysis described in Section ES.1.2, the *Wind Vision Study Scenario* was identified as a credible scenario that extends current wind deployment trends, leverages the existing domestic wind industry manufacturing base, and complements the broader literature. In the near-term (2020), the wind deployment in the *Study Scenario* is consistent with the growth found with aggressive wind cost reductions and relatively high fossil fuel prices. It also extends recent (as of 2013) deployment trends and maintains the existing domestic manufacturing base. In the mid-term (2030), the *Study Scenario* falls between modeled wind generation under aggressive cost reductions or aggressive cost

6. See Analytical Framework of the *Wind Vision* at the beginning of the Executive Summary for a brief description of the *Wind Vision Study* scenarios analyzed.

Table ES.1-2. Wind Penetration (% share of end-use demand) in *BAU Scenario, BAU Sensitivities,* and the *Study Scenario*[7]

Year	*BAU Scenario*	*BAU* Sensitivities			*Study Scenario*
		High Fossil Fuel Costs	Low Wind Costs	High Fossil Fuel Costs and Low Wind Costs	
2013 (actual)	4.5%	4.5%	4.5%	4.5%	**4.5%**
2020	7%	7%	8%	10%	**10%**
2030	10%	17%	16%	24%	**20%**
2050	25%	32%	34%	41%	**35%**

Note: Percentages characterize wind's contribution to the electric sector as a share of end-use electricity demand (net wind generation divided by consumer electricity demand).

reductions coupled to high fossil fuel prices, while continuing to build from the existing manufacturing base and maintaining consistency with the 2008 study. In the long-term (2050), the *Study Scenario* is grounded by modeled results under low wind costs—i.e., land-based wind levelized cost of electricity (LCOE) reduction of 24% by 2020, 33% by 2030, and 37% by 2050; and offshore wind LCOE reduction of 22% by 2020, 43% by 2030, 51% by 2050 (Figure ES.1-2 and Table ES.1-2.).

The *Study Scenario* is represented by wind power penetration levels, as a share of total U.S. electricity demand, of 10% by 2020, 20% by 2030, and 35% by 2050. Sensitivity analyses within the *Study Scenario,* maintaining the same wind penetration levels, are used to assess the robustness of key results and highlight the impacts of varying wind power costs and fossil fuel prices. In the *Wind Vision,* many of the results emphasize outcomes across the full range of sensitivities; however, the Executive Summary primarily presents impacts for a single *Central* case. The *Central* case, or *Central Study Scenario,* applies common inputs with the *BAU Scenario* for technology cost and performance, fuel pricing, and policy treatment, but is distinguished from that scenario by its reliance on the prescribed *Study Scenario* trajectory (10% wind penetration by 2020, 20% by 2030, and 35% by 2050).

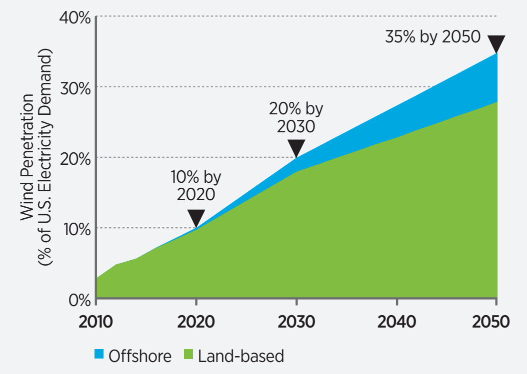
***The Study Scenario* trajectory falls within the range of credible future scenarios, identified in *BAU* and the sensitivity analyses described earlier and illustrated in Figure ES.1-2**. The *Study Scenario* seeks to understand the implications of maintaining consistency with U.S. wind installation trends and performance as well as domestic manufacturing, and leverages up-to-date insights into grid integration management and transmission capacity. Distributed wind applications[8] are not explicitly represented but are considered as part of the broader land-based capacity associated with the *Study Scenario.*

Although U.S. wind generation as of 2013 was entirely land-based, the *Wind Vision* analysis recognizes that offshore wind reached 6.5 GW globally in 2013 and an array of offshore projects in the United States are advancing through the development process. The *Study Scenario* includes explicit allocations for land-based and offshore wind (Figure ES.1-3). Near-term (through 2020) offshore contributions are estimated based on projects in advanced stages of development in the United States and on global

7. See Analytical Framework of the *Wind Vision* at the beginning of the Executive Summary for a brief description of the *Wind Vision Study* scenarios analyzed.

8. Distributed wind applications refer to wind power plants or turbines that are connected either physically or virtually on the customer side of the meter.

The *Study Scenario* consists of 10% wind generation by 2020, 20% by 2030, and 35% by 2050 compared against the *Baseline Scenario*.



Cumulative Wind Capacity (GW)		2013	2020	2030	2050
Baseline Scenario	Land-based	61			
Central Study Scenario	Land-based	61	110	202	318
	Offshore	0	3	22	86
	Total	**61**	**113**	**224**	**404**

Note: Wind capacities reported here are modeled outcomes based on the *Study Scenario* percentage wind trajectory. Results assume central technology performance characteristics. Better wind plant performance would result in fewer megawatts required to achieve the specified wind percentage, while lower plant performance would require more megawatts.

Figure ES.1-3. The *Wind Vision Study Scenario* and *Baseline Scenario*

offshore wind technology innovation projections identified in the literature. Longer-term (post-2020) contributions are based on literature projections for global growth and assume continued U.S. growth in offshore, whereby offshore wind provides 2% of U.S. electricity demand in 2030 and 7% in 2050.

Impacts from the *Study Scenario* are compared to a *Baseline Scenario* in which wind capacity is fixed at 2013 levels. The key design feature that distinguishes these scenarios is the level of wind deployment (i.e., 2013 capacity levels in the *Baseline Scenario* and respective wind capacity in the *Study Scenario* that corresponds to the trajectory of 10% wind penetration by 2020, 20% by 2030, and 35% by 2050). Resulting differences in outcomes based on this design feature (e.g., transmission expansion, electricity prices, fossil generation) are evaluated and attributed specifically to wind power deployment. Comparison with the *Baseline Scenario* enables an estimation of the incremental impact of all future (post-2013) wind deployment, including the economic and social benefits of wind.

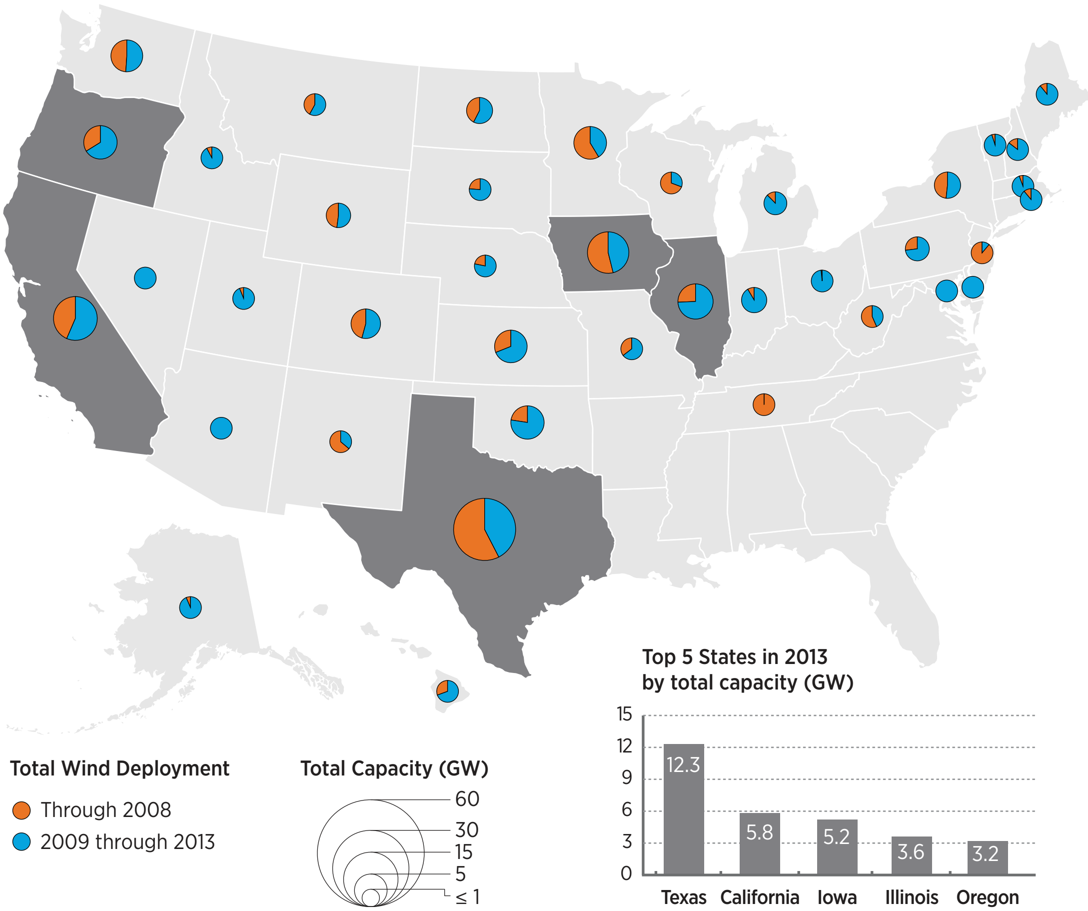
ES.2 State of the Wind Industry: Recent Progress, Status and Emerging Trends

With more than 61 GW installed across 39 states at the end of 2013, utility-scale wind power is a cost-effective source of low-emissions power generation in those regions where substantial wind potential exists. From 2008 to 2013, wind power installations expanded in geographic deployment and cumulative capacity (Figure ES.2-1), with corresponding growth in the domestic supply chain. Arizona, Delaware, Maryland and Nevada each added their first utility-scale wind projects between 2008 and 2013.

Wind power costs have declined by more than one-third since 2008 and the U.S. manufacturing base

> Wind power is becoming a mainstream power source in the U.S. electricity portfolio, supplying 4.5% of the nation's electricity demand in 2013. Since the 2008 publication of the DOE report, *20% Wind Energy by 2030,* the industry has scaled its domestic manufacturing capacity and has driven down wind power costs by more than one-third. A review of these industry developments is summarized in Chapter 2, and these insights were used to inform the modeling inputs and assumptions of the *Study Scenario.*

In 2013, cumulative utility-scale wind deployment reached 61 GW across 39 states.



Note: Distributed wind projects with less than 1 MW have been installed in all 50 states.

Figure ES.2-1. Utility-scale wind deployment through 2013

In several aspects, the wind industry has made progress since 2008 exceeding expectations from the DOE Report, *20% Wind Energy by 2030.*

	2008 Actuals	2013 Model Results Detailed in the 2008 Report, *20% Wind Energy by 2030*	2013 Actuals
Cumulative Installed Wind Capacity (GW)	25	48	61
States with Utility-Scale Wind Deployment	29	35	39
Costs (2013$/MWh)[a]	71	66	45

a. Estimated average levelized cost of electricity in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher at hub height) and excluding the federal production tax credit

Figure ES.2-2. Wind power progress since the 2008 DOE Report, *20% Wind Energy by 2030*

has expanded to support annual deployment levels growth—from 2 GW/year in 2006, to 8 GW/year in 2008, to peak installations of 13 GW/year in 2012. While the *20% Wind Scenario* from the 2008 report was not a projection for the future, the growth of wind power since 2008 exceeded the assumptions made in that report. Figure ES.2-2 lists a comparison of historical data from 2008, the 2013 outcomes in the 2008 *20% Wind Scenario,* and actual 2013 wind power statistics. The noted updates in wind power costs and supply chain capacity were used to inform the feasibility of the *Study Scenario.*

ES.2.1 Wind Power Markets and Economics

In the United States, new investments in wind plants averaged $13 billion/year between 2008 and 2013.[9] Global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21%. Although impacted by policy uncertainty and associated variability in demand, domestically manufactured content for large turbine components has increased. Domestic nacelle assembly capacity, for example, is estimated at 10 GW/year.

The combined import share of wind equipment tracked by trade codes (i.e., blades, towers, generators, gearboxes, and complete nacelles), as a fraction of total equipment-related turbine costs, declined from approximately 80% in 2006–2007 to 30% in 2012–2013. Though not all equipment is tracked, domestic content for some large, key components, such as blades and towers, ranged between 50% and 80% in 2012. Domestic content for nacelle components was significantly lower. The share of wind turbine project costs (including non-turbine equipment project costs that were sourced domestically) was approximately 60% in 2012. In 2013, the wind supply chain included more than 560 facilities across 43 states. Given the transport and logistics challenges of moving large wind turbine components over long distances, continued U.S. manufacturing and supply chain vitality is expected to be at least partially coupled to future levels of domestic demand for wind equipment. Recent fluctuations in demand and market uncertainty have forced some manufacturing facilities to furlough employees and others to cease operations altogether.

The LCOE from wind in good to excellent resource sites declined by more than one-third from 2008 to 2013, falling from $71/megawatt-hour (MWh) to

9. Unless otherwise specified, all financial results reported are in 2013$.

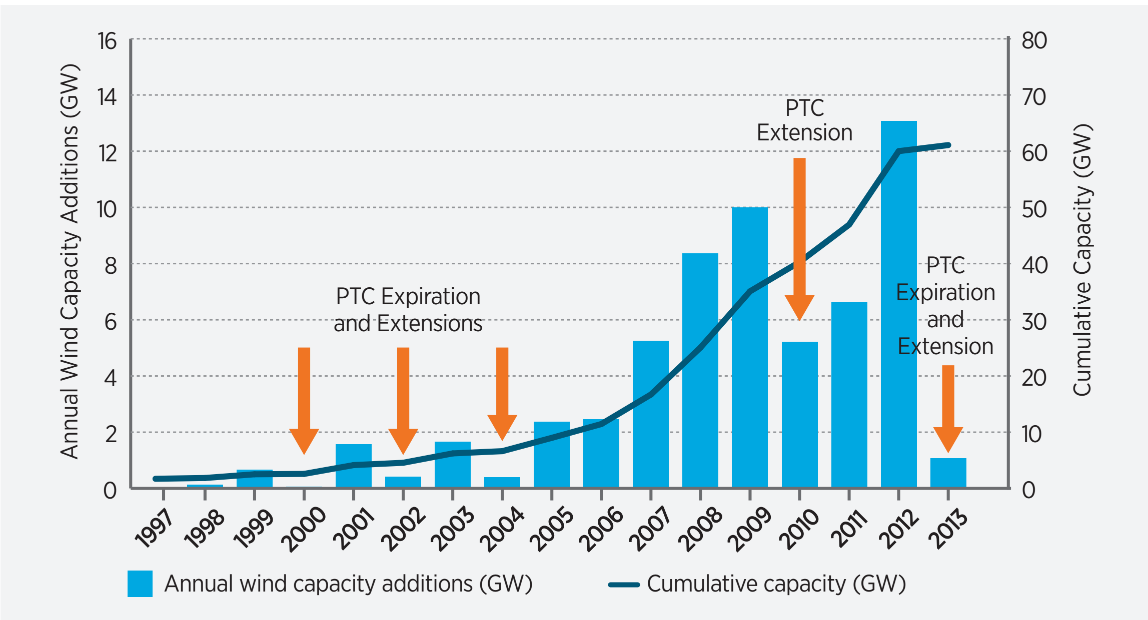
$45/MWh (Figure ES.2-2). In some markets with excellent wind resource and transmission availability, wind power sales prices are competitive with fossil generation, but significant variations are seen in the LCOE of individual wind projects. The LCOE for wind is influenced by the quality of the wind resource and access to transmission, as well as by capital and balance of system costs, plant performance and productivity, operations and maintenance (O&M) costs, and financing costs. Incentives and policies also have significant effects on power purchase agreement prices. In some regions of the country, especially those with state tax incentives, wind power prices are competitive with wholesale power prices and other new sources of generation.

Low natural gas market prices and their subsequent impacts on wholesale electricity prices, along with overall low energy growth since 2008 and a lack of long-term federal policy stability, have influenced recent levels of wind power deployment. Natural gas generation comprised 30% of end-use electricity demand in 2013, compared with 24% in 2008 and a peak of 33% in 2012. Low natural gas prices exerted downward pressure on wholesale power prices in recent years preceding 2013. Over the same period of time, electricity demand has remained relatively constant as a result of the combination of the economic recession and recovery, and improved energy efficiency. Despite these trends, robust wind deployment in the United States since 2008 has been driven by substantial advancements in wind technology and cost reductions, coupled with continued state and federal policy support. At the same time, prior expirations of federal incentives have created a boom-bust cycle for wind power (Figure ES.2-3). Because of electricity market conditions and the latest expiration of the federal production tax credit (PTC), this robust growth is not projected to continue.

ES.2.2 National Social and Economic Impacts of Wind

Local economic impacts of wind power are derived from temporary and permanent employment in construction, engineering, transportation, manufacturing, and operations; local economic activity resulting from wind construction; and increased revenues from land lease payments and tax revenue. A study of economic development impacts for wind power installations between 2000 and 2008 found

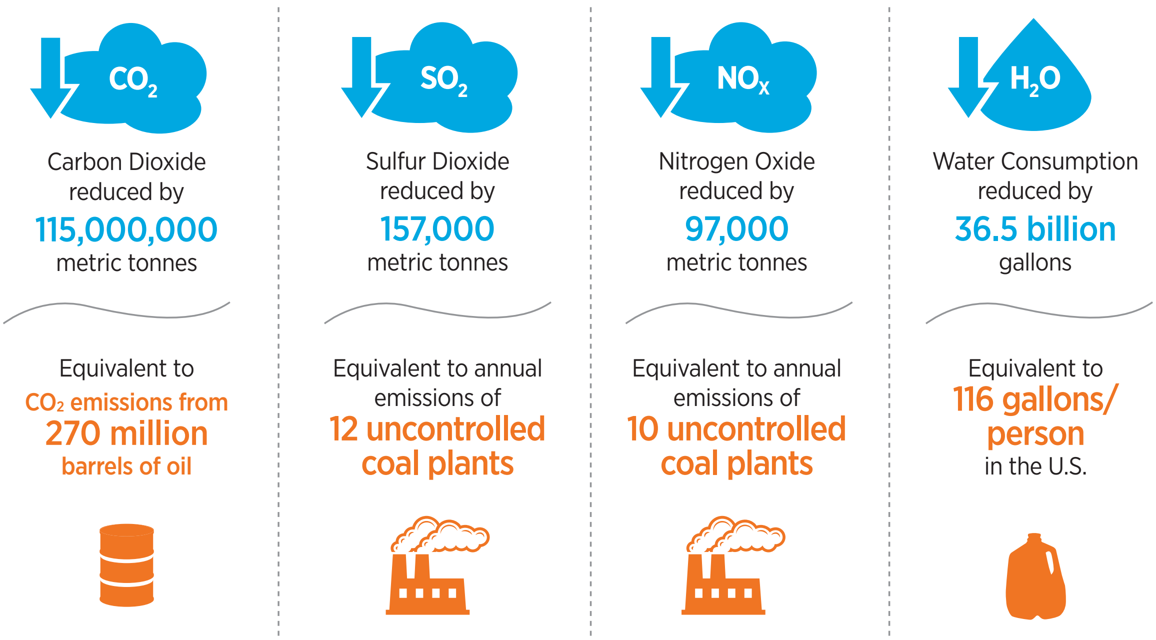
Policy uncertainty has resulted in fluctuations in historical wind deployment.



On January 1, 2014, the PTC expired again and lapsed for more than 11 months. In early December 2014, the PTC was extended again, but was valid only through year-end 2014.

Figure ES.2-3. Historical wind deployment variability and the PTC

Wind generation in 2013 provided a range of environmental benefits.



Note: Emissions and water savings calculated using the EPA's Avoided Emissions and Generation Tool (AVERT). 'Uncontrolled coal plants' are those with no emissions control technology.

Figure ES.2-4. Estimated emissions and water savings resulting from wind generation in 2013[10]

that total county personal income was 0.2% higher and employment 0.4% higher in counties with installed wind power, relative to those without wind power installations. Another study on four rural counties in west Texas found cumulative economic activity resulting from wind investments in local communities to be nearly $520,000 (2011$) per MW of installed capacity over the 20-year lifetime of the wind plant. In 2013, an estimated total of more than 50,000 onsite and supply chain jobs were supported nationally by wind investments**.**

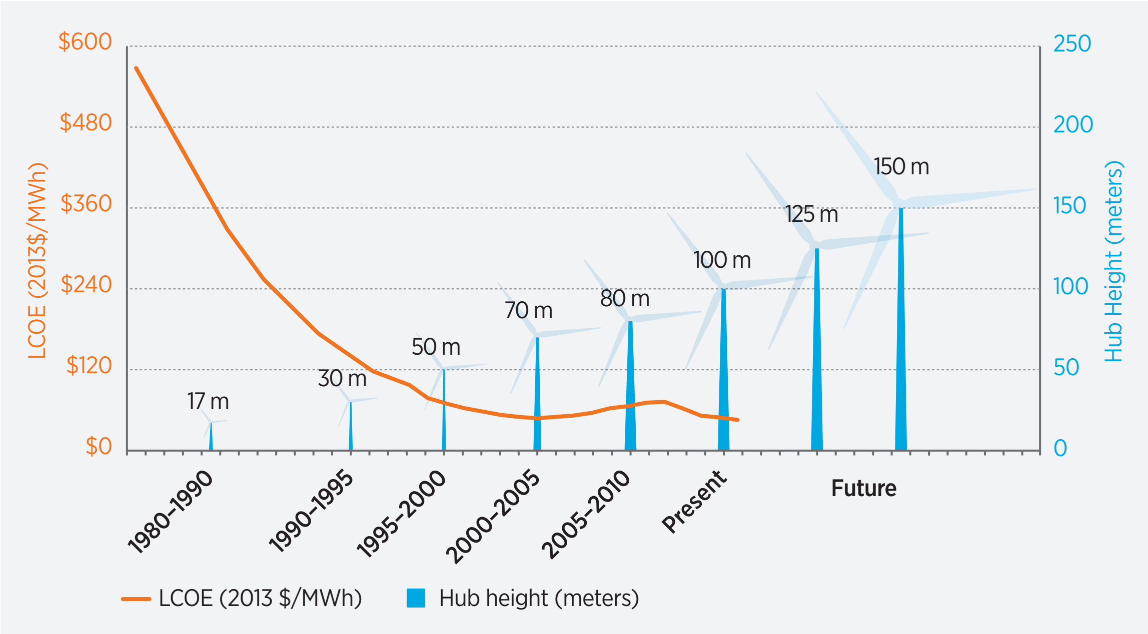
Wind deployment delivers public health and environmental benefits today, including reduced greenhouse gas (GHG) emissions, reduced air pollutants, and reduced water consumption and withdrawals. The power sector is the largest contributor to GHG emissions and a major source of criteria air pollutants such as sulfur dioxide (SO_2) and nitrous oxides (NO_X). Wind power is already reducing these emissions from the power sector (Figure ES.2-4). Future wind deployment levels will affect the magnitude of these benefits.

ES.2.3 Wind Technology, Manufacturing, and Logistics

Continued advancements and scale-up of turbine technology have helped reduce wind power costs and enable broader geographic deployment of wind power. Significant effort has been applied to improve performance and reliability of individual wind turbines. These improvements have included design of longer blades and taller towers (Figure ES.2-5), developments in innovative drive train designs, and increased use of improved controls and sensors that collectively capture energy from the wind more cost effectively. Wind technology improvements have made lower wind speed sites more economically viable, even in regions previously thought to have little or no wind potential. In 2013, wind project development was underway in nearly every U.S. state and the focus of innovation was shifting from individual turbine performance to overall plant performance characteristics, which will continue to drive down wind electricity generation costs.

10. The Clean Air Benefits of Wind Energy. Washington, DC: American Wind Energy Association. Accessed February 3, 2015: *http://www.awea.org/Advocacy/Content.aspx?ItemNumber=5552.*

Scale-up of wind technology has supported cost reductions.



Note: LCOE is estimated in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher), excluding the federal production tax credit. Hub heights reflect typical turbine model size for the time period.

Figure ES.2-5. Wind technology scale-up trends and the levelized cost of electricity

Technology advancements now center on complementing larger wind turbines with enhanced siting strategies and advanced control systems for arrays of wind turbines. A better understanding of wind resources and continued technology developments are leading trends in improved performance, increased reliability, and reduced cost of wind electricity. As turbine technology advances and components like blades and towers increase in size, transportation costs could increase and manufacturing may become more complex. The industry is working to balance costs and benefits, with innovative transport solutions across the supply chain. Continued innovation in turbine design, manufacturing, transportation, and construction can allow industry to address logistical barriers for the next generation of larger wind turbines.

Domestic manufacturing could continue to expand, provided domestic demand remains stable. Domestic wind components and skilled labor requirements will continue to be dependent on near-term domestic demand. Lack of stable domestic demand for wind power could reverse the trend of higher domestic content in wind turbine manufacturing.

ES.2.4 Wind Integration and Delivery

Large amounts of wind power are reliably and effectively integrated into the electric power system. Wind power contributed 4.5% of U.S. electricity demand and 3.2% of global electricity demand through 2013; two states, Iowa and South Dakota, exceeded 25% of in-state generation from wind in 2013; and seven other states operated with greater than 12% of their annual electricity generation from wind (Colorado, Idaho, Kansas, Minnesota, North Dakota, Oklahoma, and Oregon). Power system operators who have experience with wind now view its use routinely as a dependable component in the portfolio of generating options. Wind power has been successfully integrated into the power system and can contribute to grid management services in flexible power systems. Improved wind forecasting, wind plant controls, and expanding the geographical area for reserve sharing and demand response have all contributed to increased power system flexibility.

Many potential sites with high quality wind energy resources have minimal or no access to electrical transmission facilities. This creates a bottleneck to cost-effective wind deployment. Various efforts have yielded progress nationally on overcoming transmission barriers. For example, the Competitive Renewable Energy Zones Plan in Texas enabled transmission expansion to connect wind-rich resources in the Texas Panhandle to population centers in the central and eastern regions of the state. Prior to the Competitive Renewable Energy Zones Plan, 7 GW of wind power were operating within Texas. By early 2014, interconnection agreements had been signed for proposed projects totaling an additional 7 GW, and applications had been submitted for 24 GW of wind power. Dedicated efforts like those In Texas could be a model for transmission expansion in other regions of the country.

ES.2.5 Wind Deployment: Siting, Regulation, and Collaboration

Extensive experience and focused research have shown that adverse impacts to wildlife and local communities resulting from wind deployment need to be managed through careful siting, thoughtful public engagement, and mitigation strategies. Emphasis is now on optimizing co-existence, addressing community and regulatory concerns in the development process, and using mutually agreed-upon strategies to reduce or eliminate potential negative impacts, all while supporting responsible wind power deployment. Siting concerns are being addressed by on-going research. One example of this work is a 2014 DOE study produced by Lawrence Berkeley National Laboratory. Findings from this study indicate no statistical impact on home property values near wind facilities. Another example is a recent American Wind Wildlife Institute study that provides the most recent assessment of the avian mortality impact of wind plants. Open collaboration with a community and its leaders provides increased public involvement and understanding of best practices for both land-based and offshore wind deployment.

A number of government agencies, industry organizations, researchers, academics, non-government organizations, and collaborative groups are working to address wind-related issues, from permitting and environmental oversight to manufacturing and workforce training. Work by collaborative groups has shifted from the basic sharing of information and best practices to active engagement aimed at solving specific problems at the local, regional, and national levels. Example collaborative bodies in this effort include the American Wind Wildlife Institute, the Bats and Wind Energy Cooperative, the National Wind Coordinating Collaborative, and the Utility Variable-Generation Integration Group. These parties have enhanced education to help stakeholders understand the role and impact of wind on the energy market, communities, and the environment.

The wind power community has addressed substantive siting and regulatory issues, and continues to work closely with regulatory organizations to streamline regulatory processes. Requirements can vary widely by state, locality, site ownership and oversight, project size, grid interconnection, and other project attributes. As a result, wind power projects across the country must adhere to different and changing regulatory standards, leaving uncertainties in development timelines and increasing risks to successful project development.

ES.3 Costs, Benefits, and Other Impacts of the *Study Scenario*

The *Wind Vision* analysis considered an array of impacts for the *Study Scenario* (10% wind penetration by 2020, 20% by 2030, and 35% by 2050) relative to the *Baseline Scenario*. Modeling inputs for these scenarios are consistent with those applied in the prior *BAU Scenario* and sensitivities (see Table ES.1-1) except wind power deployment is fixed at *Study Scenario* levels. Under *BAU* conditions, wind power deployment occurs if and where wind power is economically competitive. In the *Study Scenario,* wind deployment begins in 2013 at 61 GW and then is added in future years to reach levels of 10% wind penetration by 2020, 20% by 2030, and 35% by 2050. In the *Baseline Scenario,* wind power deployment begins in 2013 at 61 GW and then remains fixed at 61 GW for all future years. Although the *Study Scenario* does not precisely replicate the prior *BAU* or related sensitivity outcomes, aggressive wind cost reductions (land-based wind LCOE reduction of 24% by 2020, 33% by 2030, and 37% by 2050 and offshore wind LCOE reduction of 22% by 2020, 43% by 2030, 51% by 2050), high fossil fuel prices (e.g., $3/MMBtu coal price and $7/MMBtu electric sector natural gas price), or various combinations of the two could support the level of wind penetration achieved in the *Study Scenario.*

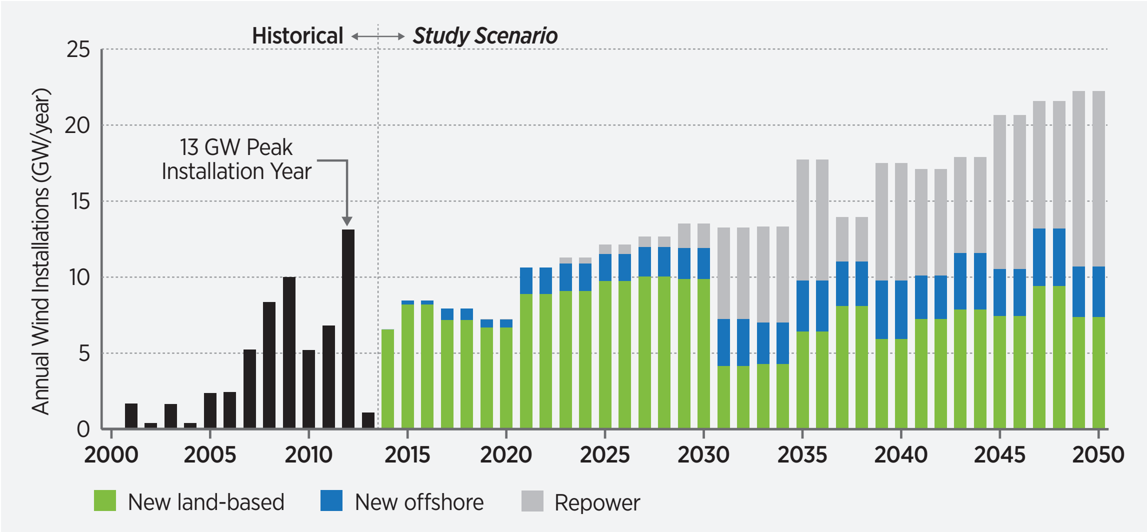
ES.3.1 Wind Industry and Electric Sector Impacts

In the *Central Study Scenario*, total installed wind capacity increases from the 61 GW installed at year-end 2013 to approximately 113 GW by 2020, 224 GW by 2030, and 404 GW by 2050. This growth represents nearly three doublings of installed capacity and includes all wind market segments: land-based, distributed, and offshore wind. Of these installed capacity amounts, offshore wind comprises 3 GW, 22 GW, and 86 GW for 2020, 2030, and 2050, respectively. The amount of installed capacity needed to meet the deployment levels considered in the *Study Scenario* will depend on future wind technologies. For example, with improvements in wind technology yielding higher capacity factors, only 382 GW of wind capacity is needed to reach the 35% penetration level in 2050. Conversely, 459 GW would be required using today's technologies without further advancements. Growth in the *Study Scenario* utilizes approximately 5% of the available land-based wind resource (after exclusions for environmentally sensitive or other protected areas) and 5.5% of the available offshore wind resource of the nation.

The *Study Scenario* supports new capacity additions at levels comparable to the recent (as of 2013) past, but drives increased demand for new wind turbine equipment as a function of repowering needs. Demand for wind turbines averages approximately 8 GW/year from 2014 to 2020 and 12 GW/year from 2021 to 2030, and increases to 18 GW/year from 2031 to 2050. While aggregate demand trends upward (Figure ES.3-1), it is primarily concentrated in the new land-based segment in the near-term. Deployment of offshore plants and repowering (the replacement of turbine equipment at the end of its useful life with new state-of-the-art turbine equipment) become more significant segments of the industry in the 2031–2050 timeframe.

Although electricity rates increase by 1% between 2020 and 2030, the *Central Study Scenario* results in a net savings of $149 billion relative to the *Baseline Scenario* for the period of 2013–2050. Savings are incurred from 2031 to 2050 as fossil fuel prices trend upward and aging power infrastructure requires replacement. Increasing wind generation to the levels of the *Study Scenario* simultaneously reduces carbon dioxide (CO_2) emissions, improves air quality resulting in lower levels of illness and premature loss of life, and reduces demand on water resources, among other impacts.

The *Study Scenario* results in relatively constant new capacity additions but also supports increased demand for turbines due to repowering.



Note: New capacity installations include capacity added at a new location to increase the total cumulative installed capacity or to replace retiring capacity elsewhere. Repowered capacity reflects turbine replacements occurring after plants reach their useful lifetime. Wind installations shown here are based on model outcomes for the *Central Study Scenario* and do not represent projected demand for wind capacity.

Figure ES.3-1. Historical and forward-looking wind power capacity in the *Central Study Scenario*

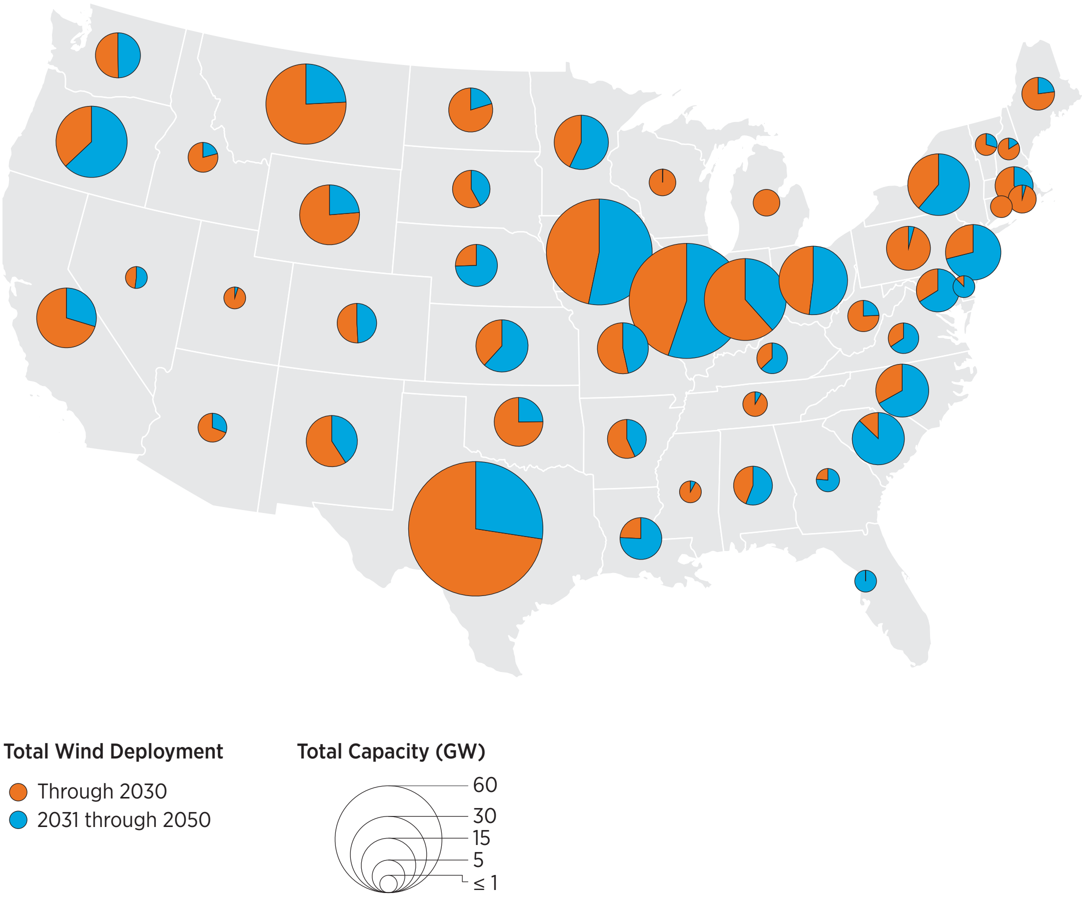
In the *Study Scenario,* wind industry expenditures (new capital and development expenditures, annual operating expenditures, and repowered capital expenditures) grow to more than $30 billion/year from 2020 to 2030, and are estimated at approximately $70 billion/year by 2050. By 2050, annual expenditures exceed $20 billion/year for operations, $25 billion/year for repowering, and $25 billion/year for new greenfield development.

The *Study Scenario* suggests continued geographical diversity in wind power deployment. Figure ES.3-2 illustrates the state-level distribution of utility-scale wind capacity (land-based and offshore) in 2030 and 2050 under the *Central Study Scenario*. By 2030, installed wind capacity exists in all but one state, with 37 states having more than 1 GW of capacity. By 2050, wind capacity exists in all 50 states, with 40 states having more than 1 GW of installed wind capacity. As of 2013, wind installations of 62 MW and 206 MW exist in Alaska and Hawaii respectively. While future wind deployment in these states is expected and could potentially grow beyond 1 GW, these states are not counted among the states with more than 1 GW in 2030 or 2050 because the modeling analysis was restricted to the 48 contiguous states.

Variations in wind resource quality, relative distances to load centers, and existing infrastructure drive regional differences in modeled wind penetration levels. Based on model outcomes from the *Study Scenario,* most of the western and central parts of the United States have penetration levels that exceed the 10% nationwide level by 2020, with some regions approaching or exceeding 30% penetration. By 2050, wind penetration levels exceed 40% across much of the West and upper Midwest, with less substantial—but still sizeable—levels in other parts of the country. In the Southeast, wind penetration levels are lower than in other regions, but are significantly higher than levels found in that region in 2013, particularly for coastal areas.

The levels of wind penetration examined in the *Study Scenario* increase variability and uncertainty in electric power system planning and operations (Figure ES.3-3). From the perspective of planning reserves, wind power's aggregated capacity value in the *Study Scenario* was about 10–15% in 2050 (with lower marginal capacity value), thereby reducing the ability of wind compared to other generators to contribute to increases in peak planning reserve requirements. In addition, the uncertainty introduced by wind in the *Study Scenario* increased the level of operating reserves that must be maintained by the system. Transmission constraints result in average curtailment of 2–3% of wind generation, modestly increasing the threshold for economic wind deployment. These costs are embedded in the system costs and retail rate impacts noted below. Such challenges can be mitigated by various means including increased system flexibility, greater electric system coordination, faster dispatch schedules, improved forecasting, demand response, greater power plant cycling, and—in some cases—storage options. Specific circumstances dictate the optimal solution. Continued research is expected to provide more specific and localized assessments of impacts.

The *Study Scenario* results in broad-based geographic distribution of wind capacity.



Note: Results presented are for the *Central Study Scenario*. Across *Study Scenario* sensitivites, deployment by state may vary depending on changes in wind technology, regional fossil fuel prices, and other factors. ReEDS model decision-making reflects a national optimization perspective. Actual distribution of wind capacity will be affected by local, regional, and other factors not fully represented here. Alaska and Hawaii cannot be currently modeled in ReEDS but will contribute to overall wind deployment.

Figure ES.3-2. *Study Scenario* distribution of wind capacity by state in 2030 and 2050

The *Study Scenario* includes impacts that will require investments by the wind industry and the electric sector at large.

Industry Investment	Deployment	Integration[b]	Transmission[c]	Offshore Wind
• 8–11 GW/year average net capacity additions throughout the 2013–2050 period • 18 GW/year annual turbine demand as more wind plants are repowered from 2031 to 2050 • $70 billion/year[a] by 2050 annual wind industry investment from new capacity additions, repowered capacity, and operations and maintenance	• 404 GW of cumulative capacity by 2050 for 35% wind energy • All 50 states with wind deployment by 2050 • 37 states by 2030 and 40 by 2050 with more than 1 GW of wind power (within the contiguous United States)	• Increased system flexibility is required, but can be acquired from many sources • 2–3% average curtailment of annual wind generation; estimated wind capacity value of 10–15% by 2050 • Integration solutions required, but will vary by region	• 2.7x incremental transmission needs by 2030; 4.2x by 2050 • 10 million MW-miles incremental transmission capacity required by 2030 Cumulatively 29 million incremental MW-miles required by 2050 • Through 2020: incremental 350 circuit miles/year needed 2021–2030: incremental 890 circuit miles/year, and 2031–2050: incremental 1,050 circuit miles/year	• Established U.S. offshore wind market and supply chain by 2020 • 22 GW installed by 2030 and 86 GW installed by 2050 • By 2050, offshore wind in multiple regions, including the East Coast, West Coast, Great Lakes, and Gulf of Mexico

a. Expenditures in 2013$

b. Increased costs associated with greater demand for system flexibility and wind curtailments are embedded in the system costs and retail rate impacts reported in Chapter 3.

c. All transmission estimates reported are the incremental difference between the *Study Scenario* and *Baseline Scenario*. Estimated circuit miles assume a single circuit 345 kV transmission line with a nominal carrying capacity of 900 MW. ReEDS transmission capacity additions exclude those added for reliability purposes only and conductor replacement on existing infrastructure. Estimates shown here represent point to point transfers, for which explicit corridors have not been identified.

Figure ES.3-3. Summary of wind industry and other electric sector impacts in the *Central Study Scenario*

Table ES.3-1. Transmission Impacts in the *Central Study Scenario*

	Historical Average	2014–2020	2021–2030	2031–2050	Cumulative 2014–2050
Study Scenario MW-miles (change from *Baseline Scenario*)		311,000/year	801,000/year	949,000/year	29,000,000
Study Scenario circuit miles (change from *Baseline Scenario*)[a]	870/year	350/year	890/year	1,050/year	33,000
		By 2020	**By 2030**	**By 2050**	
Ratio of *Study Scenario* to *Baseline Scenario*		1.5x	2.7x	4.2x	

Note: ReEDS transmission capacity additions exclude those added for reliability purposes only and conductor replacement on existing infrastructure. Estimates shown here represent point to point transfers, for which explicit corridors have not been identified.

a. Assuming a representative transmission line with a carrying capacity of 900 MW, typical for single-circuit 345 kV lines

Required new transmission capacity for the *Central Study Scenario* is 2.7 times greater in 2030 than for the respective *Baseline Scenario,* and about 4.2 times greater in 2050. Transmission expenditures are less than 2% of total electric sector costs in the *Central Study Scenario* (Table ES.3-1). Incremental cumulative (2013 and on) transmission needs of the *Central Study Scenario* relative to the *Baseline Scenario* amount to 10 million MW-miles by 2030 and 29 million MW-miles by 2050. Assuming only single-circuit 345-kilovolt lines (with a 900-MW carrying capacity) are used to accomplish this increase, an average of 890 circuit miles/year of new transmission lines would be needed between 2021 and 2030, and 1,050 miles/year between 2031 and 2050. This is comparable with the average of 870 circuit miles added each year since 1991 (as of 2013).[11] New transmission capacity in the *Study Scenario* is primarily concentrated in the Midwest and southern Central regions of the United States.

In the *Study Scenario*, wind primarily displaces fossil fuel-fired generation, especially natural gas, with the amount of displaced gas growing over time. In the long-term (after 2030), wind in the *Study Scenario* also affects the growth of other renewable generation and, potentially, future growth of nuclear generation. The avoided generation mix will ultimately depend on uncertain future market conditions, including fossil fuel prices and technology costs. Displaced fossil fuel consumption leads to avoided emissions and other social impacts. With wind penetration increasing to the levels envisioned under the *Study Scenario,* the fossil fleet's role to provide energy declines while its role to provide reserves increases.

11. Transmission estimates for the *Study Scenario* exclude maintenance for the existing grid, reliability-driven transmission, and other factors that would be similar between the *Baseline Scenario* and the *Study Scenario*.

ES.3.2 Costs of the *Wind Vision Study Scenario*

National average retail electricity prices for both the *Baseline Scenario* and the *Study Scenario* are estimated to grow (in real terms) between 2013 and 2050. Through 2030, retail electricity prices of the *Central Study Scenario*, relative to the *Baseline Scenario*, are less than 1% higher. In the long-term (2050), retail electricity prices are expected to be lower by 2%. A wider range of future costs and savings are possible as estimated by the sensitivity scenarios (Table ES.3-2). In 2020, retail electricity rates range from nearly zero cost difference up to a 1% cost increase when comparing the *Study Scenario* to the *Baseline Scenario.* In 2030, incremental costs are estimated to be as high as a 3% cost under the most unfavorable conditions for wind (low fossil fuel prices combined with high wind power costs). Under the most favorable conditions in 2030, the *Study Scenario* results in a 2% reduction in retail electricity prices relative to the *Baseline Scenario.* By 2050, incremental electricity prices of all sensitivities of the *Study Scenario* are estimated to range from a 5% increase to a 5% savings in electricity prices over all cases for the corresponding *Baseline Scenario.*

Relative to the *Baseline Scenario,* the *Central Study Scenario* results in an approximately 1% increase in retail electricity rates in the near-term (2020) to mid-term (2030), but cost savings by 2050. On a cumulative net present value basis, the long-term system cost reductions outweigh near- and mid-term cost increases across most conditions analyzed.

On an annual basis, the impacts on electricity consumers in the *Central Study Scenario* are estimated to include costs of $2.3 billion (0.06¢/kilowatt-hour [kWh]) compared to the *Baseline Scenario* in 2020, costs of $1.5 billion (0.03¢/kWh) in 2030, and savings of $13.7 billion (0.28¢/kWh) in 2050 (Table ES.3-2). Across the range of sensitivities, annual consumer impacts range from cost increases of $0.8 billion to $3.6 billion in 2020, savings of $12.3 billion to costs of $14.6 billion in 2030, and savings of $31.5 billion to costs of $26.9 billion in 2050. Electricity costs and savings driven by future wind deployment will depend strongly on future technology and fuel price conditions.

Table ES.3-2. Change in Electricity Prices for the *Study Scenario* Relative to the *Baseline Scenario*

	2020	2030	2050
Central Study Scenario electricity price (change from *Baseline Scenario*)	0.06¢/kWh cost (+0.6%)	0.03¢/kWh cost (+0.3%)	0.28¢/kWh savings (-2.2%)
Central Study Scenario annual electricity consumer costs (change from *Baseline Scenario*)	$2.3 billion costs	$1.5 billion costs	$13.7 billion savings
Study Scenario sensitivity range (% change from *Baseline Scenario*)	+0.2% to + 0.9%	-2.4% to +3.2%	-5.1% to +4.8%
Study Scenario annual electricity consumer costs range (change from *Baseline Scenario*)	$0.8 to $3.6 billion costs	$12.3 billion savings to $14.6 billion costs	$31.5 billion savings to $26.9 billion costs

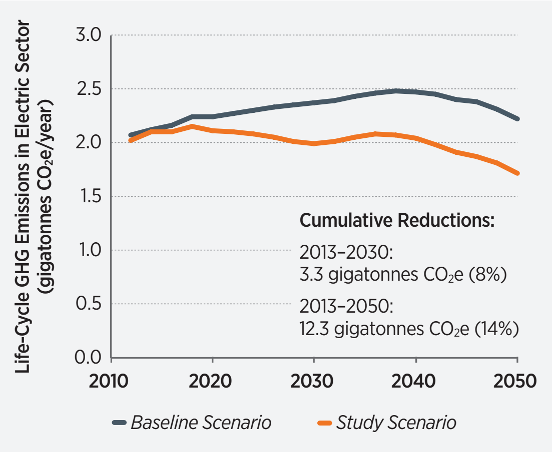
Note: Expenditures in 2013$

In present value terms, cumulative electric sector expenditures (fuel, capital, operating, and transmission) are lower for the *Study Scenario* than for the *Baseline Scenario* under Central conditions and many sensitivities. From 2013 to 2050, the *Central Study Scenario* results in cumulative present value (3% real discount rate) savings of approximately $149 billion (-3%). Potential electricity sector expenditures range from savings of $388 billion (-7%) to a cost increase of $254 billion (+6%), depending on future wind power cost trends and fossil fuel prices.

ES.3.3 Benefits of the *Study Scenario*

The *Central Study Scenario* reduces electric sector life-cycle GHG emissions by 6% in 2020 (0.13 gigatonnes CO_2-equivalents), 16% in 2030 (0.38 gigatonnes CO_2-equivalents), and 23% in 2050 (0.51 gigatonnes CO_2-equivalents), compared to the *Baseline Scenario*. Cumulative GHG emissions are reduced by 12.3 gigatonnes CO_2-equivalents from 2013 to 2050 (14%) (Figure ES.3-4). Based on the U.S. Interagency Working Group's Social Cost of Carbon estimates, these reductions yield global avoided climate change damages estimated at $85–$1,230 billion, with a central estimate of $400 billion (2013–2050 discounted present value). This

Life-cycle GHG emissions are lower in the *Central Study Scenario* than in the *Baseline Scenario*.



Note: Life-cycle GHG emissions consider upstream emissions (e.g., manufacturing and raw materials), ongoing combustion and non-combustion emissions, and downstream emissions (e.g., decommissioning).

Figure ES.3-4. Lifecycle GHG emissions in the *Central Study Scenario* and *Baseline Scenario*

The *Central Study Scenario* results in a 16% reduction in carbon dioxide (CO_2) emissions by 2030 and 23% by 2050 from the electricity sector, relative to the *Baseline Scenario.* Other air pollutants affecting public health also decrease and water savings accrue in many regions of the country, including arid water-stressed regions in the Southwest. The estimated value of CO_2 reductions ranges from $85–$1,230 billion, while reductions in other air pollutants are valued at $52–$272 billion.

is equivalent to a benefit of wind energy that ranges from 0.7¢–10¢/kWh of wind, with a central benefit estimate of 3.2¢/kWh of wind.

The *Central Study Scenario* results in reductions in other air pollutants (e.g., PM, SO_2, and NO_x), yielding societal health and environmental benefits that range from $52–$272 billion (2013–2050, discounted present values) depending on the methods of quantification. The majority of the benefits come from reduced premature mortality due to reductions in SO_2 emissions in the eastern United States. In total, the health and environmental benefits are equivalent to a benefit of wind energy that ranges from 0.4¢/kWh of wind to 2.2¢/kWh of wind. Table ES.3-3 highlights some of the air pollution benefits.

Table ES.3-3. Health Benefits in 2050 of Reduced Air Pollution in the *Central Study Scenario*

Type of Benefit	Amounts
Cumulative monetized benefits (2013$)	$108 billion
Avoided premature deaths	21,700
Avoided emergency room visits for asthma due to $PM_{2.5}$ effects	10,100
Avoided school loss days due to ozone effects	2,459,600

Note: Central estimate results are presented, which follow the 'EPA Low' methodology for calculating benefits, further detailed in Chapter 3. Monetized benefits are discounted at 3%, but mortality and morbidity values are simply accumulated over the 2013–2050 time period. Health impacts presented here are a subset of those analyzed. $PM_{2.5}$ is particulate matter of diameter 2.5 microns or less. The full set of results is presented in detail in Chapter 3.

The *Central Study Scenario* results in reduced national electric-sector water withdrawals (1% in 2020, 4% in 2030, and 15% in 2050) and water consumption (4% in 2020, 11% in 2030, and 23% in 2050) compared to the *Baseline Scenario*. Anticipated reductions, relative to the *Baseline Scenario,* exist in many parts of the United States, including the water-stressed arid states in the Southwest (Figure ES.3-5). Reductions in water use driven by the *Study Scenario* would have environmental and economic benefits, and would help reduce competition for scarce water resources.

The value of reduced GHG and air pollution emissions in the *Central Study Scenario* relative to the *Baseline Scenario* exceeds the under 1% cost increase in electricity rates in 2020 and 2030. By 2050, the *Central Study Scenario* results in savings across all three categories—electricity rates, GHG emissions, and air pollution emissions (Figure ES.3-6). Savings are also incurred on a cumulative basis across all three metrics (Figure ES.3-7). The range of GHG benefits was estimated following the Interagency Working Group's Social Cost of Carbon methodology and varying discount rates. The range of air pollution benefits was calculated following methodologies of the U.S. Environmental Protection Agency (EPA) and the Air Pollution Emission Experiments and Policy model, known as AP2. Several other categories of impacts such as water use are analyzed but not monetized, due to a lack of established peer-reviewed, national-scale methodologies.

Electric sector water consumption is 23% lower in the *Central Study Scenario* relative to the *Baseline Scenario* by 2050.

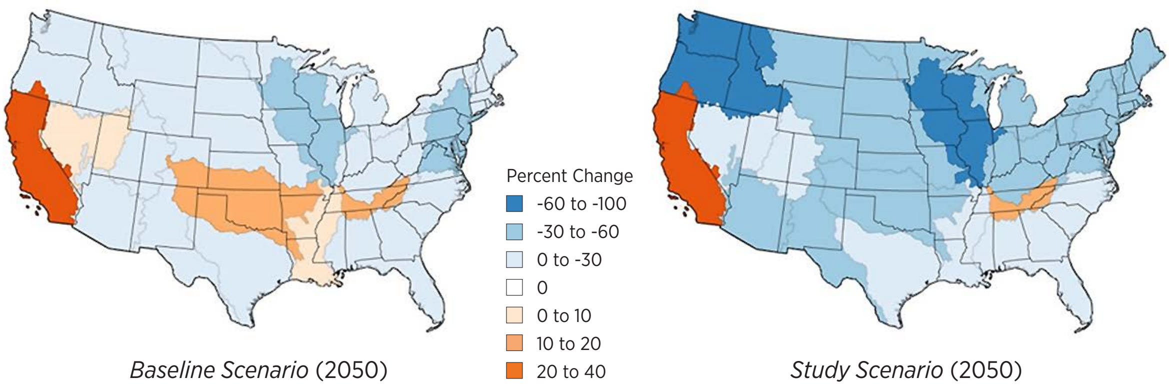
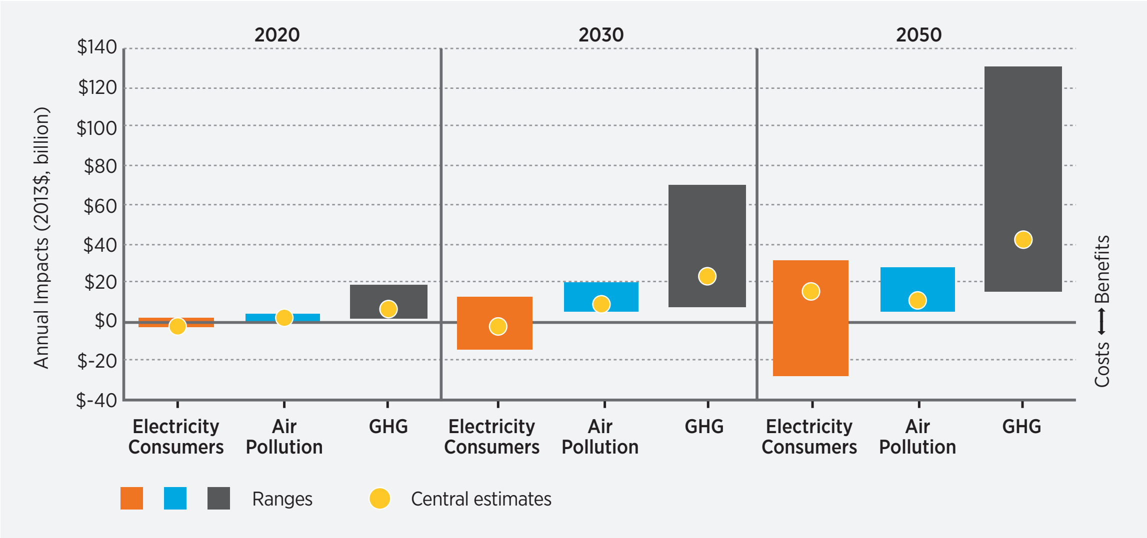


Figure ES.3-5. Change in water consumption used in electricity generation from 2013 to 2050 for the *Baseline Scenario* and *Central Study Scenario*

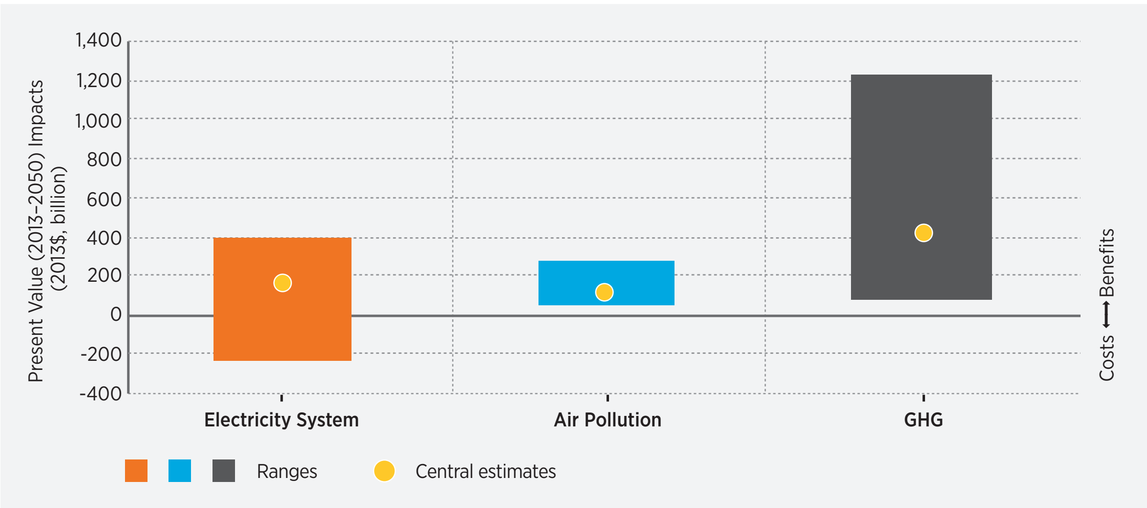
Reduced GHG, SO_2, NO_X, and fine particulate matter emissions provide benefits in 2020, 2030, and 2050 in addition to the savings in electricity rates achieved in the *Central Study Scenario* by 2050.



Note: Results represent the annual incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario.* Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity consumers costs range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

Figure ES.3-6. Monetized impacts of the *Study Scenario* relative to the *Baseline Scenario* in 2020, 2030, and 2050

On a present value (2013–2050) basis, the *Central Study Scenario* results in electricity system cost savings relative to the *Baseline Scenario,* in addition to the benefits of reduced air pollution and GHG emissions.



Note: Results represent the present value of incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario.* Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity system cost range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

Figure ES.3-7. Cumulative (2013-2050) present value of monetized impacts of the *Study Scenario* relative to the *Baseline Scenario*

ES.3.4 Additional Impacts Associated with the *Study Scenario*

Other impacts from the *Study Scenario* include reduced sensitivity (20% less) to future fossil fuel price volatility, support for a vibrant wind industry supply chain (526,000–670,000 jobs by 2050), and increased tax revenue and lease payments to local communities. In addition, the *Study Scenario* results in manageable but non-trivial impacts to land use, local wildlife populations, and host communities.

The *Study Scenario* contributes to a reduction in both long-term natural gas price risk and natural gas prices, compared to the *Baseline Scenario*. The *Central Study Scenario* results in total electric system costs that are 20% less sensitive to long-term fluctuations in coal and natural gas prices (Figure ES.3-8). Additionally, the *Central Study Scenario* leads to a potential $280 billion in consumer savings due to reduced natural gas prices outside the electric sector, equivalent to a levelized consumer benefit from wind energy of 2.3¢/kWh of wind.

The *Study Scenario* supports a robust domestic wind industry, with wind-related gross jobs from investments in new and operating wind plants ranging from 201,000–265,000 in 2030 and increasing to 526,000–670,000 in 2050 (Figure ES.3-8). Actual future wind-related jobs (on-site, supply chain, and induced) will depend on the future strength of the domestic supply chain and additional training and educational programs as necessary.

Wind project development examined in the *Wind Vision* affects local communities through land lease payments and local property taxes. Under the *Central Study Scenario,* wind power capacity additions lead to land-based lease payments that increase from $350 million in 2020 to $650 million in 2030, to $1,020 million in 2050. Offshore wind lease payments increase from $15 million in 2020 to $110 million in 2030, to $440 million in 2050. Property tax payments associated with wind projects are estimated to be $900 million in 2020; $1,770 million in 2030; and $3,200 million in 2050.

Under the *Central Study Scenario,* the land area occupied by turbines, roads, and other infrastructure equates to 0.03% of total land area in the contiguous United States in 2030 and 0.04% in 2050. This land area equates to less than one-third of total land area occupied by U.S. golf courses in 2013. Total land area occupied by wind plants in 2050 (accounting for requisite turbine spacing and typical densities) equates to less than 1.5% of the total land area in the contiguous United States.

Continued wind deployment will need to account for the potential impacts on avian, bat, and other wildlife populations; the local environment; the landscape; and communities and individuals living in proximity to wind projects. Continued research, technological solutions (e.g., strategic operational strategies and wildlife deterrents), and experience are anticipated to make siting and mitigation more effective and efficient.

The *Study Scenario* results in cumulative savings, benefits, and an array of additional impacts by 2050.

System Costs[a]	Benefits[b,c]		
$	GHG	Air Pollution	H_2O
$149 billion (3%) lower cumulative electric sector expenditures	14% reduction in cumulative GHG emissions (12.3 gigatonnes CO_2-equivalents), saving $400 billion in avoided global damages	$108 billion savings in avoided mortality, morbidity, and economic damages from cumulative reductions in emissions of SO_2, NO_X, and PM 21,700 premature deaths from air pollution avoided	23% less water consumption and 15% less water withdrawals for the electric power sector

Additional Impacts

Energy Diversity	Jobs	Local Revenues	Land Use	Public Acceptance and Wildlife
Increased wind power adds fuel diversity, making the overall electric sector 20% less sensitive to changes in fossil fuel costs. The predictable, long-term costs of wind power create downward price pressure on fossil fuels that can cumulatively save consumers $280 billion from lower natural gas prices outside the electric sector.	Approximately 600,000 wind-related gross jobs spread across the nation.	$1 billion in annual land lease payments $440 million annual lease payments for offshore wind plants More than $3 billion in annual property tax payments	Less than 1.5% (106,000 km^2) of contiguous U.S. land area occupied by wind power plants Less than 0.04% (3,300 km^2) of contiguous U.S. land area impacted by turbine pads, roads, and other associated infrastructure	Careful siting, continued research, thoughtful public engagement, and an emphasis on optimizing coexistence can support continued responsible deployment that minimizes or eliminates negative impacts to wildlife and local communities

Note: Cumulative costs and benefits are reported on a Net Present Value basis for the period of 2013 through 2050 and reflect the difference in impacts between the *Central Study Scenario* and the *Baseline Scenario*. Results reported here reflect central estimates within a range; see Chapter 3 for additional detail. Financial results are reported in 2013$ except where otherwise noted.

a. Electric sector expenditures include capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled, but excludes consideration of estimated benefits (e.g., GHG emissions).

b. Morbidity is the incidence of disease or rate of sickness in a population.

c. Water consumption refers to water that is used and not returned to the source. Water withdrawals are eventually returned to the water source.

Figure ES.3-8. Summary of costs, benefits, and other outcomes associated with the *Study Scenario* relative to the *Baseline Scenario* by 2050

ES.3.5 Impacts Specific to Offshore and Distributed Wind

The *Study Scenario* contributions from offshore wind are characterized by an industrial base that evolves from its nascent state in 2013 to one that can supply more than 80 GW of offshore capacity by 2050. This deployment represents just 5.5% of the resource potential for offshore areas adjacent to the 28 coastal and Great Lakes states. Under this scenario, the offshore wind industry would complement and bolster a strong land-based industry through the use of common supply chain components and the development of workforce synergies.

The cost of offshore wind needs to be aggressively reduced. Through innovation and increasing scale, however, this market segment could bring notable potential benefits. In particular, offshore wind offers the ability to reduce wholesale market power clearing prices and consumer costs in transmission-congested coastal areas, supports local jobs and port development opportunities, and offers geographic proximity to densely populated coastal regions with limited renewable power alternatives.

Distributed wind applications, including customer-sited wind and wind turbines embedded in distribution networks, offer a number of unique and relevant attributes. On-site distributed wind turbines allow farmers, schools, and other energy users to benefit from reduced utility bills, predictable costs, and a hedge against the possibility of rising retail electricity rates. At the same time, decentralized generation such as distributed wind can benefit the electrical grid. Distributed wind also supports a domestic market; U.S. suppliers dominate the domestic small wind turbine market with 93% of 2013 sales on a unit basis and 88% on a capacity basis. These suppliers also maintain domestic content levels of 80–95% for turbine and tower hardware and are well positioned to capitalize on export opportunities, including the growing demand for decentralized electricity around the globe.

ES.4 The Wind Vision Roadmap: A Pathway Forward

The roadmap was developed through a collaborative effort led by DOE, with contributions and rigorous peer review from industry, the electric power sector, environmental stewardship organizations, academia, national labs, and participants at various levels of government. It defines specific top-level activities for all major stakeholder sectors, including the wind industry, the wind research community, and others. Though the roadmap includes actions intended to inform analysis of various policy options, it is beyond the scope and purview of the *Wind Vision* to suggest policy preferences or recommendations, and no attempt is made to do so.

> The *Wind Vision* includes a detailed roadmap of technical and institutional actions necessary to overcome the challenges to wind power making a significant contribution to a cleaner, low-carbon, domestic energy economy.

The objective of the *Wind Vision* roadmap is to identify the challenges and actions necessary to increase the opportunities for U.S. wind deployment. This portfolio of actions (Chapter 4 and Appendix M) builds upon the successes of wind power to date and addresses remaining gaps. The actions cover the major domestic wind applications on land (including distributed applications) and offshore. Additionally, the roadmap provides a framework from which others can define specific activities at greater levels of detail.

The *Wind Vision Study Scenario* was created for the purpose of examining costs and benefits. Although it represents a potential future for wind growth, it is unlikely to be realized without continued technology and systems improvements. In aggregate, the roadmap actions are a series of steps that can be expected to increase the likelihood of achieving wind power growth at the levels considered in the *Study Scenario.*

ES.4.1 Core Roadmap Actions

Optimizing wind contributions requires coordination among multiple parties who can implement a set of complementary approaches around three agreed-upon themes (Table ES.4-1):

1. **Reduce Wind Costs:** Chapter 3 of the *Wind Vision* report indicates that the costs associated with the *Study Scenario* can be reduced across the range of sensitivities with wind cost reductions. Accordingly, reductions in LCOE are a priority focus. This theme includes actions to reduce capital costs; reduce annual operating expenses; optimize annual energy production and reduce curtailment and system losses; reduce financing expenses; reduce grid integration and operating expenses; and reduce market barrier costs, including regulatory and permitting, environmental, and radar mitigation costs.
2. **Expand Developable Areas:** Expansion of wind power into high-quality resource areas is also important for realizing the *Study Scenario* at cost levels described in Chapter 3 of the *Wind Vision* report. Key actions within this theme include actions to expand transmission; responsibly expand developable geographic regions and sites; improve the potential of low-wind-speed locales; improve the potential of ocean and Great Lakes offshore regions; improve the potential in areas requiring careful consideration of wildlife, aviation, telecommunication, or other environmental issues; and improve the potential of high wind resource locations that have poor access to electricity transmission infrastructure. National parks, densely populated locations, and sensitive areas such as federally designated critical habitat are generally excluded from the roadmap actions, since they are likely not to be developed as wind sites.
3. **Increase Economic Value for the Nation:** The *Study Scenario* projects substantial benefits for the nation, but additional steps are needed to ensure these benefits are realized and maximized. This theme includes actions to provide detailed and accurate data on costs and benefits for decision makers; grow and maintain U.S. manufacturing throughout the supply chain; train and hire a U.S. workforce; provide diversity in the electricity generating portfolio; and provide a hedge against fossil fuel price increases. The overall aim is to ensure that wind power continues to provide enduring value for the nation.

High-level roadmap actions are summarized in Text Box ES.4-1 and explained in detail in the *Wind Vision* report (Chapter 4 and Appendix M). These core roadmap actions fall into nine action areas: wind power resources and site characterization; wind plant technology advancement; supply chain, manufacturing, and logistics; wind power performance, reliability, and safety; wind electricity delivery and integration; wind siting and permitting; collaboration, education, and outreach; workforce development; and policy analysis.

The roadmap is the beginning of an evolving, collaborative, and necessarily dynamic process. The *Wind Vision* roadmap is not prescriptive. It does not detail how suggested actions are to be accomplished; it is left to the responsible organizations to determine the optimum timing and sequences of specific activities. It suggests an approach of continual updates to assess impacts and redirect activities as necessary and appropriate through 2050. These updates, which are intended to be conducted at least every two years, would be informed by analysis and would ensure that the roadmap adapts to changing technology, market, and political factors.

The *Wind Vision* depicts a future in which wind power has the potential to be a significant contributor to a cost-effective, reliable, low-carbon U.S. energy portfolio. Optimizing U.S. wind power's impact and value will require strategic planning and continued contributions across a wide range of stakeholders, such as state and federal agencies and government, utility companies, equipment research and development organizations, manufacturers, national laboratories, and academic institutions. Bringing these participants together on a regular basis to revisit this roadmap and update priorities will be essential to maintaining and sustaining focus on wind power's long-term future for the nation.

Table ES.4-1. Roadmap Strategic Approach

Core Challenge	**Wind has the potential to be a significant and enduring contributor to a cost-effective, reliable, low carbon, U.S. energy portfolio. Optimizing U.S. wind power's impact and value will require strategic planning and continued contributions across a wide range of participants.**		
Key Themes	**Reduce Wind Costs** Collaboration to reduce wind costs through wind technology capital and operating cost reductions, increased energy capture, improved reliability, and development of planning and operating practices for cost-effective wind integration.	**Expand Developable Areas** Collaboration to increase market access to U.S. wind resources through improved power system flexibility and transmission expansion, technology development, streamlined siting and permitting processes, and environmental and competing use research and impact mitigation.	**Increase Economic Value for the Nation** Collaboration to support a strong and self-sustaining domestic wind industry through job growth, improved competitiveness, and articulation of wind's benefits to inform decision making.
Issues Addressed	Continuing declines in wind power costs and improved reliability are needed to improve market competition with other electricity sources.	Continued reduction of deployment barriers as well as enhanced mitigation strategies to responsibly improve market access to remote, low wind speed, offshore, and environmentally sensitive locations.	Capture the enduring value of wind power by analyzing job growth opportunities, evaluating existing and proposed policies, and disseminating credible information.
***Wind Vision Study Scenario* Linkages**	Levelized cost of electricity reduction trajectory of 24% by 2020, 33% by 2030, and 37% by 2050 for land-based wind power technology and 22% by 2020, 43% by 2030, and 51% by 2050 for offshore wind power technology to substantially reduce or eliminate the near- and mid-term incremental costs of the *Study Scenario*.	Wind deployment sufficient to enable national wind electricity generation shares of 10% by 2020, 20% by 2030, and 35% by 2050.	A sustainable and competitive regional and local wind industry supporting substantial domestic employment. Public benefits from reduced emissions and consumer energy cost savings.
Roadmap Action Areas[a]	• Wind Power Resources and Site Characterization • Wind Plant Technology Advancement • Supply Chain, Manufacturing, and Logistics • Wind Power Performance, Reliability, and Safety • Wind Electricity Delivery and Integration • Wind Siting and Permitting • Collaboration, Education, and Outreach • Workforce Development • Policy Analysis	• Wind Power Resources and Site Characterization • Wind Plant Technology Advancement • Supply Chain, Manufacturing, and Logistics • Wind Electricity Delivery and Integration • Wind Siting and Permitting • Collaboration, Education, and Outreach • Policy Analysis	• Supply Chain, Manufacturing, and Logistics • Collaboration, Education, and Outreach • Workforce Development • Policy Analysis

a. Several action areas address more than one key theme.

Text Box ES-1.

High-Level Wind Vision Roadmap Actions

1 Wind Power Resources and Site Characterization

Action 1.1 – Improve Wind Resource Characterization. Collect data and develop models to improve wind forecasting at multiple temporal scales—e.g., minutes, hours, days, months, years.

Action 1.2 – Understand Intra-Plant Flows. Collect data and improve models to understand intra-plant flow, including turbine-to-turbine interactions, micro-siting, and array effects.

Action 1.3 – Characterize Offshore Wind Resources. Collect and analyze data to characterize offshore wind resources and external design conditions for all coastal regions of the United States, and to validate forecasting and design tools and models at heights at which offshore turbines operate.

2 Wind Plant Technology Advancement

Action 2.1 – Develop Next-Generation Wind Plant Technology. Develop next-generation wind plant technology for rotors, controls, drivetrains, towers, and offshore foundations for continued improvements in wind plant performance and scale-up of turbine technology.

Action 2.2 – Improve Standards and Certification Processes. Update design standards and certification processes using validated simulation tools to enable more flexibility in application and reduce overall costs.

Action 2.3 – Improve and Validate Advanced Simulation and System Design Tools. Develop and validate a comprehensive suite of engineering, simulation, and physics-based tools that enable the design, analysis and certification of advanced wind plants. Improve simulation tool accuracy, flexibility, and ability to handle innovative new concepts.

Action 2.4 – Establish Test Facilities. Develop and sustain world-class testing facilities to support industry needs and continued innovation.

Action 2.5 – Develop Revolutionary Wind Power Systems. Invest research and development (R&D) into high-risk, potentially high-reward technology innovations.

3 Supply Chain, Manufacturing and Logistics

Action 3.1 – Increase Domestic Manufacturing Competitiveness. Increase domestic manufacturing competitiveness with investments in advanced manufacturing and research into innovative materials.

Action 3.2 – Develop Transportation, Construction, and Installation Solutions. Develop transportation, construction and installation solutions for deployment of next-generation, larger wind turbines.

Action 3.3 – Develop Offshore Wind Manufacturing and Supply Chain. Establish domestic offshore manufacturing, supply chain, and port infrastructure.

4 Wind Power Performance, Reliability, and Safety

Action 4.1 – Improve Reliability and Increase Service Life. Increase reliability by reducing unplanned maintenance through better design and testing of components, and through broader adoption of condition monitoring systems and maintenance.

Action 4.2 – Develop a World-Class Database on Wind Plant Operation under Normal Operating Conditions. Collect wind turbine performance and reliability data from wind plants to improve energy production and reliability under normal operating conditions.

Action 4.3 – Ensure Reliable Operation in Severe Operating Environments. Collect data, develop testing methods, and improve standards to ensure reliability under severe operating conditions including cold weather climates and areas prone to high force winds.

Action 4.4 – Develop and Document Best Practices in Wind O&M. Develop and promote best practices in operations and maintenance (O&M) strategies and procedures for safe, optimized operations at wind plants.

Action 4.5 – Develop Aftermarket Technology Upgrades and Best Practices for Repowering and Decommissioning. Develop aftermarket upgrades to existing wind plants and establish a body of knowledge and research on best practices for wind plant repowering and decommissioning.

Continues next page

Text Box ES-1. *(Continued)*

High-Level Wind Vision Roadmap Actions

5 Wind Electricity Delivery and Integration

Action 5.1 – Encourage Sufficient Transmission. Collaborate with the electric power sector to encourage sufficient transmission to deliver potentially remote generation to electricity consumers and provide for economically efficient operation of the bulk power system over broad geographic and electrical regions.

Action 5.2 – Increase Flexible Resource Supply. Collaborate with the electric power sector to promote increased flexibility from all resources including conventional generation, demand response, wind and solar generation, and storage.

Action 5.3 – Encourage Cost-Effective Power System Operation with High Wind Penetration. Collaborate with the electric power sector to encourage operating practices and market structures that increase cost-effectiveness of power system operation with high levels of wind power.

Action 5.4 – Provide Advanced Controls for Grid Integration. Optimize wind power plant equipment and control strategies to facilitate integration into the electric power system, and provide balancing services such as regulation and voltage control.

Action 5.5 – Develop Optimized Offshore Wind Grid Architecture and Integration Strategies. Develop optimized subsea grid delivery systems and evaluate the integration of offshore wind under multiple arrangements to increase utility confidence in offshore wind.

Action 5.6 – Improve Distributed Wind Grid Integration. Improve grid integration of and increase utility confidence in distributed wind systems.

6 Wind Siting and Permitting

Action 6.1 – Develop Mitigation Options for Competing Human Use Concerns. Develop impact reduction and mitigation options for competing human use concerns such as radar, aviation, maritime shipping, and navigation.

Action 6.2 – Develop Strategies to Minimize and Mitigate Siting and Environmental Impacts. Develop and disseminate relevant information as well as minimization and mitigation strategies to reduce the environmental impacts of wind power plants, including impacts on wildlife.

Action 6.3 – Develop Information and Strategies to Mitigate the Local Impact of Wind Deployment and Operation. Continue to develop and disseminate accurate information to the public on local impacts of wind power deployment and operations.

Action 6.4 – Develop Clear and Consistent Regulatory Guidelines for Wind Development. Streamline regulatory guidelines for responsible project development on federal, state, and private lands, as well as in offshore areas.

Action 6.5 – Develop Wind Site Pre-Screening Tools. Develop commonly accepted standard siting and risk assessment tools allowing rapid pre-screening of potential development sites.

7 Collaboration, Education, and Outreach

Action 7.1 – Provide Information on Wind Power Impacts and Benefits. Increase public understanding of broader societal impacts of wind power, including economic impacts; reduced emissions of carbon dioxide, other greenhouse gases, and chemical and particulate pollutants; less water use; and greater energy diversity.

Action 7.2 – Foster International Exchange and Collaboration. Foster international exchange and collaboration on technology R&D, standards and certifications, and best practices in siting, operations, repowering, and decommissioning.

8 Workforce Development

Action 8.1 – Develop Comprehensive Training, Workforce, and Educational Programs. Develop comprehensive training, workforce, and education programs, with engagement from primary schools through university degree programs, to encourage and anticipate the technical and advanced-degree workforce needed by the industry.

9 Policy Analysis

Action 9.1 – Refine and Apply Energy Technology Cost and Benefit Evaluation Methods. Refine and apply methodologies to comprehensively evaluate and compare the costs, benefits, risks, uncertainties, and other impacts of energy technologies.

Action 9.2 – Refine and Apply Policy Analysis Methods. Refine and apply policy analysis methodologies to understand federal and state policy decisions affecting the electric sector portfolio.

Action 9.3 – Maintain the Roadmap as a Vibrant, Active Process for Achieving the Wind Vision Study Scenario. Track wind technology advancement and deployment progress, prioritize R&D activities, and regularly update the wind roadmap.

ES.4.2 Risk of Inaction

Without actions to improve wind's competitive position in the market, such as those described in the roadmap and summarized in Text Box ES.4-1, the nation risks losing its existing wind manufacturing infrastructure and a range of public benefits as illustrated in the *Wind Vision*. The analytical results in Chapter 3 of the *Wind Vision* report reveal significant cumulative health, carbon, environmental, and other social benefits deriving from the penetration levels of the *Wind Vision Study Scenario.* Reduced economic activity and increased energy efficiency measures have slowed the growth of electricity demand and reduced the need for new generation of any kind. This decreased need for new generation, in combination with decreased natural gas costs and other factors, has reduced demand for new wind plants. Absent actions that address these trends, a loss of domestic manufacturing capacity is expected and the potential benefits associated with the *Study Scenario* may not be realized.

Although it is outside the scope of this report, one of the core challenges of the *Study Scenario* is that current policies and market economics at the end of 2013 lack mechanisms to recognize the full value of low-carbon generation. The actions in the roadmap can help reduce the costs of low-carbon electricity generation from wind, ultimately lowering the cost of curbing future emissions and complementing any low-carbon policies enacted.

ES.5 Conclusions

One of the greatest challenges for the 21st century is producing and making available clean, affordable, and secure energy for the United States. Wind power can be a substantial part of addressing that challenge. The *Wind Vision* demonstrates that wind can be deployed at high penetrations with economics that are compelling. Although the wind industry has adopted improved technology and exhibited growth in the years leading up to 2013, the path that allowed the industry to serve 4.5% of current U.S. end-use electricity demand is different from the path needed to achieve 10% by 2020, 20% by 2030, and 35% by 2050. A new strategy and updated priorities are needed to provide positive outcomes for future generations.

The *Wind Vision* report highlights the national opportunity to capture domestic energy as well as environmental and economic benefits with accelerated and responsible deployment of advanced wind power technologies across all U.S. market sectors and regions. It quantifies the associated costs and benefits of this deployment and provides a roadmap for the collaboration needed for successful implementation. Carrying out the *Wind Vision* roadmap actions will also provide cost reductions in the implementation of any future policy measures.

ES.5.1 The Opportunity

The *Wind Vision* analysis modeled a future *Study Scenario* (with various sensitivities) in which 10% of the nation's electricity demand is met by wind power in 2020, 20% by 2030, and 35% by 2050. The near-term (2020) and mid-term (2030) incremental costs associated with large-scale deployment of wind are less than 1% with most scenarios. Over the long term (through 2050), the *Study Scenario* offers net savings to the electric power sector and electricity consumers.

Increasing wind power can simultaneously deliver an array of benefits to the nation that address issues of national concern, including climate change, air quality, public health, economic development, energy diversity, and water security. For example, the 12.3 gigatonnes of CO_2-equivalents avoided over the period 2013–2050 in the *Central Study Scenario* delivers $400 billion in savings for avoided global damages. This is equivalent to a benefit of 3.2¢/kWh of U.S. wind energy produced. The value of long-term social benefits such as these can be provided by wind energy and far exceeds the initial investment required.

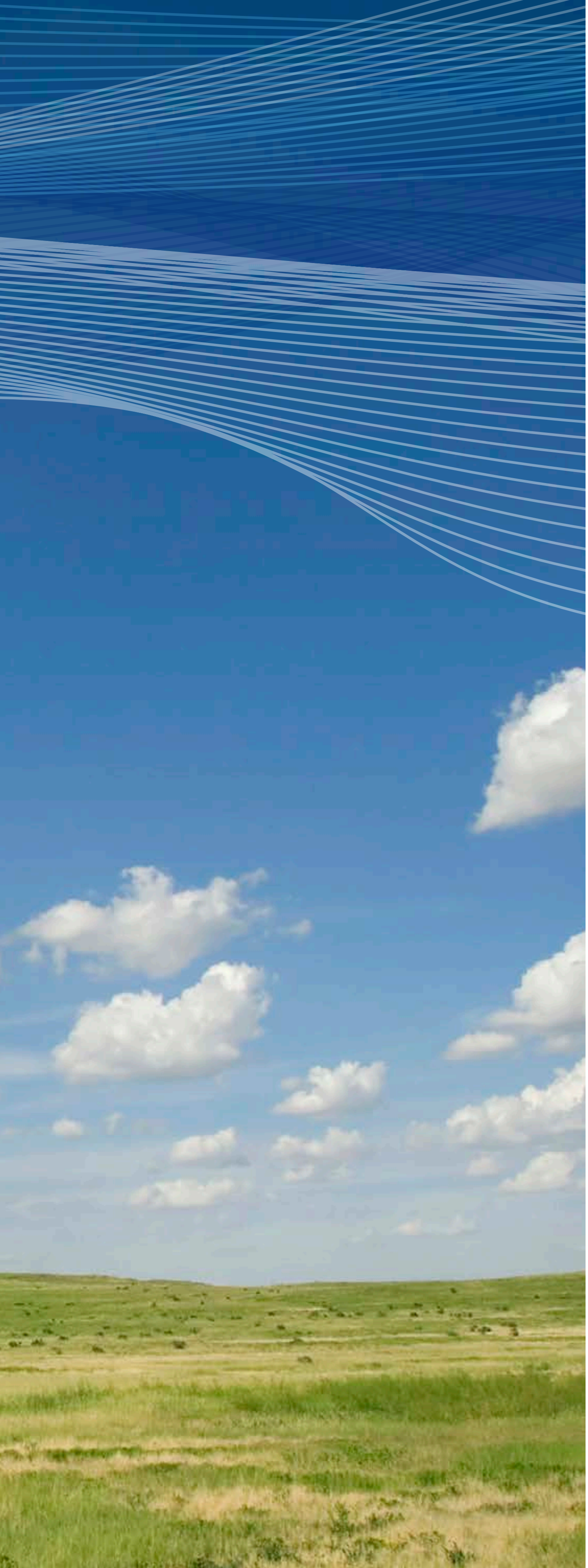
ES.5.2 The Challenge

While the wind industry is maturing, many future actions and efforts remain critical to further advancement of domestic wind energy. Continued technology development is essential to minimizing costs in the near term and maximizing savings in the long term. Shifts in bulk power market and institutional practices could ease delivery and integration of even higher penetrations of wind power. Engagement with the public, regulators, and local communities can enable wind energy deployment to proceed with minimal negative impacts and applicable benefits to host communities and local wildlife. Continued research and analysis on energy policy as well as wind costs, benefits, and impacts is important to provide accurate information to policymakers and the public discourse. Finally, a commitment to regularly revisit the *Wind Vision* roadmap and update priorities across stakeholder groups and disciplines is essential to ensuring a robust wind future.

ES.5.3 Moving Forward

The *Wind Vision* roadmap identifies a high-level portfolio of new and continued actions and collaborations across many fronts to help the United States realize significant long-term benefits and protect the nation's energy, environmental, and economic interests. Near-term and mid-term investments, such as those experienced in the years leading up to 2013, are needed. These investments are more than offset by long-term savings and social benefits. Stakeholders and other interested parties needs to take the next steps in refining, expanding, operationalizing, and implementing the high-level roadmap actions. These steps could be developed in formal working groups or informal collaborations and will be critical in overcoming the challenges, capitalizing on the opportunities, and realizing the national benefits detailed within the *Wind Vision*.

Photo from iStock 3865179



1 Introduction to the *Wind Vision*

Summary

The *Wind Vision* consists of four components:

1. **Documentation of the current state of wind power in the United States and identification of key accomplishments and trends over the decade leading up to 2014 (Chapter 2);**
2. **Exploration of the potential for wind power to contribute to the future electricity needs of the nation, including objectives such as reduced carbon emissions, improved air quality, and reduced water use (Chapter 3);**
3. **Quantification of costs, benefits, and other impacts associated with continued deployment and growth of U.S. wind power (Chapter 3); and**
4. **Identification of actions and future achievements that could support continued growth in the use and application of wind-generated electricity (Chapter 4).**

The *Wind Vision* and its associated analysis represent a technical update and expansion of a U.S. Department of Energy (DOE) report published in 2008, *20% Wind Energy by 2030—Increasing Wind Energy's Contribution to U.S. Electricity Supply*[1] (hereafter referred to as *20% Wind Energy by 2030*). Major changes have occurred in the electric power sector since the 2000s, when *20% Wind Energy by 2030* was published. In particular, there have been substantial reductions in existing and projected fuel costs for natural gas-fired electric generation, as well as significant reductions in the cost of energy from wind power and other renewable power technologies. Given these changes, DOE's Wind and Water Power Technologies Office initiated the *Wind Vision* study in 2013, soliciting wide-ranging participation from relevant stakeholder groups including the wind business, technology, and research communities; the electric power sector; environmental and energy-related non-governmental organizations; regulatory bodies; and government representatives at the federal and state levels.

The primary analysis of the *Wind Vision* centers on a future scenario in which wind energy serves 10% of the nation's end-use demand by 2020, 20% by 2030, and 35% by 2050. This scenario, called the *Wind Vision Study Scenario,* was identified as an ambitious but credible scenario after conducting a series of exploratory scenario modeling runs. This modeling used *Business-as-Usual* conditions (federal and state policy conditions that were current on January 1, 2014, and market data from the Energy Information Administration's Annual Energy Outlook 2014) while varying inputs such as fossil fuel costs and wind costs.

This analysis demonstrated a broad array of potential futures for U.S. wind power, including outcomes comparable to the *Study Scenario* under conditions favorable for wind deployment. The credibility of the *Study Scenario* trajectory was further validated after considering current U.S. manufacturing capacity and industry investments, and reviewing broader literature analyses of future scenarios with high levels of renewable electricity.

In order to quantify costs, benefits, and other impacts of future wind deployment, the outcomes of the *Study Scenario* are compared against those of a reference *Baseline Scenario* that fixes installed wind capacity at year-end 2013 levels of 61 gigawatts (GW). The *Baseline Scenario* and the *Study Scenario* are not goals or future projections for wind power. Rather, they comprise an analytical framework that supports detailed analysis of potential costs, benefits, and other impacts associated with future wind deployment. These three scenarios —*Study Scenario, Baseline Scenario,* and *Business-as-Usual Scenario*—are summarized below and constitute the primary analytical framework of the *Wind Vision.*

Analytical Framework of the *Wind Vision*	
Wind Vision Study Scenario	The *Wind Vision Study Scenario,* or *Study Scenario*, applies a trajectory of 10% of the nation's end-use demand served by wind by 2020, 20% by 2030, and 35% by 2050. It is the primary analysis scenario for which costs, benefits, and other impacts are assessed. The *Study Scenario* comprises a range of cases spanning plausible variations from central values of wind power and fossil fuel costs. The specific *Study Scenario* case based on those central values is called the *Central Study Scenario*.
Baseline Scenario	The *Baseline Scenario* applies a constraint of no additional wind capacity after 2013 (wind capacity fixed at 61 GW through 2050). It is the primary reference case to support comparisons of costs, benefits, and other impacts against the *Study Scenario*.
Business-as-Usual Scenario	The *Business-as-Usual (BAU) Scenario* does not prescribe a wind future trajectory, but instead models wind deployment under policy conditions current on January 1, 2014. The *BAU Scenario* uses demand and cost inputs from the Energy Information Administration's *Annual Energy Outlook 2014*.

Note: Percentages characterize wind's contribution to the electric sector as a share of end-use electricity demand (net wind generation divided by consumer electricity demand).

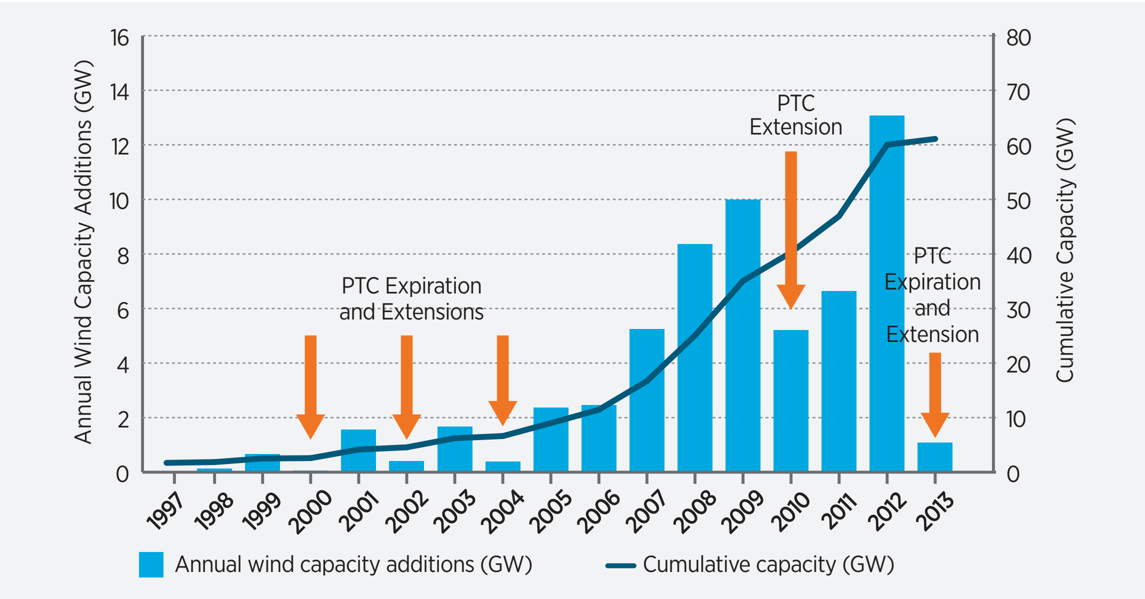
1.0 *Wind Vision*—Historical Context

Wind has been used as a source of power for millennia; historical records show that wind has been harnessed to power sailing vessels since before 3,000 B.C. Experimentation with electricity generation from wind first emerged in the late 19th century, but it was not until the 1970s that wind power began to gain visibility as a potential source of commercial power generation. In the United States, commercial power production from wind first occurred in California in the 1980s. More widespread adoption of commercial wind power generation started in the late 1990s, when declining costs, state and federal policy provisions, and a period of volatility in natural gas fuel prices launched the modern era of U.S. wind power. Electric system operators and utilities now routinely consider wind power as part of a diverse generation portfolio [2, 3, 4, 5].

As of 2013, wind power was one of the fastest-growing sources of new electricity supply. U.S. electricity demand served by wind energy had tripled, increasing from 1.5% of total end-use demand in 2008 to 4.5% in 2013 [6]. From 2008 to 2013, wind power constituted nearly 33% of all U.S. electric capacity additions and, from 2000 to 2013, installed capacity increased at a rate of nearly 30% per year [7]. As of year-end 2013, the United States wind power fleet stood at 61 GW of operating capacity [8]. The U.S. was also the top country globally for wind power generation in 2013, in terms of total wind power electricity generated [9], and ranked second globally for total wind capacity installed [7].

As of 2013, wind power was one of the fastest-growing sources of new electricity supply. U.S. electricity demand served by wind energy had tripled, increasing from 1.5% of total end-use demand in 2008 to 4.5% in 2013.

Despite growth of wind power in the United States, wind remains a relatively new contributor to the nation's power portfolio and has an uncertain future. Low natural gas prices and reduced demand for electricity have lowered wholesale power prices since 2008, making it more difficult for sources such as wind to compete in wholesale markets under 2013 market pricing mechanisms. Limited growth in electricity demand since 2008 has reduced investment in new electric generation of all types, including wind power.



On January 1, 2014, the PTC expired again and lapsed for more than 11 months. In early December 2014, the PTC was extended again, but was valid only through year-end 2014.

Figure 1–1. Historical wind deployment variability and the PTC

Uncertainty about federal support for wind power is also hampering investment [10, 11, 12]. The impact of this policy uncertainty was demonstrated in 2013, as 1.1 GW of new capacity was brought online in that year [8] without federal policy support, as compared to 13.1 GW in 2012 [7] with federal policy support. Figure 1-1 illustrates the boom-bust cycle created by expirations and late extensions or renewals of the federal production tax credit (PTC). As a result of these trends and conditions, independent projections suggest that annual wind capacity additions could fall to levels that are 50% below the 2009–2013 five-year average and 75% below the peak installation year of 2012 in the latter half of the 2010–2020 decade [13, 14, 15, 16].[1]

Projected reductions in demand for wind power could have varied consequences. Of particular significance is the potential loss of domestic wind manufacturing capacity and, in turn, U.S. wind industry jobs. Reduced near-term wind industry investment could also affect the feasibility and costs of achieving reductions in power sector emissions (i.e., carbon dioxide, sulfur dioxide, and nitrogen oxide).

In this context, DOE initiated the *Wind Vision*. Led by the Wind and Water Power Technologies Office within DOE's Office of Energy Efficiency and Renewable Energy, the *Wind Vision* represents a collaboration of more than 250 energy experts with an array of specialties. This includes the wind industry, grid operators, science-based organizations, academia, government agencies, and environmental stewardship organizations.

The *Wind Vision* consists of four components:

1. Documentation of the current state of wind power in the United States and identification of key accomplishments and trends over the decade leading up to 2014 (Chapter 2);
2. Exploration of the potential for wind power to contribute to the future electricity needs of the nation, including objectives such as reduced carbon emissions, improved air quality, and reduced water use (Chapter 3);
3. Quantification of costs, benefits, and other impacts associated with continued deployment and growth of U.S. wind power (Chapter 3); and
4. Identification of actions and future achievements that could support continued growth in the use and application of wind-generated electricity (Chapter 4).

Text Box 1-1.

Snapshot of the Wind Business in 2013

- Total wind capacity nationwide was 61 GW [6].
- Wind provided 4.5% of U.S. electricity end-use demand [6].
- 39 states had utility-scale wind projects; all 50 states had distributed wind projects [8].
- 17 states generated wind electricity in excess of 5% of their in-state generation; of these, 9 states exceed 12%, and Iowa and South Dakota both produced more than 25% of their in-state generation from wind [6].
- Several major electric utility system operators received nearly 10% or more of their electricity from wind power [3, 4].
- The wind business directly supported more than 50,500 jobs, with some 17,400 jobs in manufacturing spread over 43 states [8].
- The domestically-manufactured content of wind equipment installed in the United States increased over the previous decade, and was higher for large components such as blades, towers, and turbine assembly [7].

The findings detailed here and in subsequent chapters of the *Wind Vision* report explore each of these facets with the intention of informing policy makers, the public, and others on the impacts and potential of wind power for the United States.

Analysis, modeling inputs, and conclusions were generated by DOE with support from the national laboratories and are based on the best available information from the fields of science, technology, economics, finance, and engineering, as well as

1. Wind deployments are expected to be consistent in 2015 with historical levels due to a provision in the latest federal tax credit extension that allows for projects under construction by year-end 2013 to qualify for the production tax credit, which formally expired on December 31, 2013. Accordingly, the full impact of the recent federal tax credit expiration is not anticipated in the market until 2016. The five-year average annual installation rate (from 2009–2013) is approximately 7.3 GW per year, while peak annual installed capacity exceeded 13 GW in 2012.

historical experience gained from a decade of industry growth and maturation. The *Wind Vision* report, particularly its assessment of costs and benefits, is intended to facilitate informed discussions among various stakeholder groups including energy sector decision makers; the wind power business, technology, and research communities; the electric power sector; and the general public about the future of wind power.

The *Wind Vision* and its associated analysis represent a technical update and expansion of a DOE report published in 2008, *20% Wind Energy by 2030—Increasing Wind Energy's Contribution to U.S. Electricity Supply* [1] (hereafter referred to as *20% Wind Energy by 2030*). The 2008 report was motivated by key issues at that time, including the technical feasibility of a scenario in which 20% of the nation's electricity demand is served by wind energy and the general magnitude of impacts associated with large-scale wind deployment. To address these complex questions, DOE—together with the domestic wind industry and representative organizations from the electric power, academia, and environmental sectors—conducted a thorough feasibility assessment from 2006 to 2008, resulting in the *20% Wind Energy by 2030* report.

The *Wind Vision* and its associated analysis represent a technical update and expansion of a DOE report published in 2008, *20% Wind Energy by 2030—Increasing Wind Energy's Contribution to U.S. Electricity Supply*

Since publication, results and conclusions of the 2008 study have been a valuable resource for wind development. The major points of *20% Wind Energy by 2030* are summarized in Appendix B. Of particular significance is that, as of year-end 2013, many of the 2008 report's modeled outcomes for 2013 have been surpassed, including those around wind power deployment rates and costs (Figure 1-2; see also Appendix B). The Text Box 1-1 provides a snapshot of the wind industry as of 2013.

	2008 Actuals	2013 Model Results Detailed in the 2008 Report, *20% Wind Energy by 2030*	2013 Actuals
Cumulative Installed Wind Capacity (GW)	25	48	61
States with Utility-Scale Wind Deployment	29	35	39
Costs (2013$/MWh)[1]	71	66	45

1. Estimated average levelized cost of electricity in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher at hub height) and excluding the federal production tax credit.

Figure 1–2. Wind power progress since the 2008 DOE report, *20% Wind Energy by 2030*

1.1 Key Trends Motivating the *Wind Vision*

Major changes have occurred in the electric power sector since the early 2000s. In particular, there have been substantial reductions in the current and projected fuel costs for natural gas-fired electric generation, as well as significant reductions in the cost of energy from wind power and other renewable power technologies. These and other trends (documented in Chapter 2) affect the relative economic and environmental position of wind power in the portfolio of available generation options. In this context, an updated evaluation of the long-term potential for wind power and a new assessment of the possible contributions and impacts of future wind deployment are needed to inform planning and decision making.

1.1.1 Wind Business Evolution

Global investment in renewable power and fuels has increased five-fold since the early 2000s [17]. Public and private investment in wind has facilitated technology advancements that support record low costs and opened previously marginal resource areas to commercial wind power development. In particular, increases in wind turbine sizes and heights have contributed to improvements in energy production per unit of capacity. Since 2009, wind technology gains have been coupled with falling equipment prices, providing the conditions for an overall reduction in contracted prices for wind power of more than 50% [7].

Wind power resources at the national, regional, and local levels are better understood than in the past, and experience with siting and permitting of new land-based wind plants has grown since the mid-2000s. Enhanced wind resource characterization is enabling more informed investments into areas most likely to support viable wind power projects. Experience gained in permitting has facilitated more informed decision making by developers, local communities, and regulators, although it has also illuminated persistent challenges. Improved clarity in regulatory requirements and the application of lessons learned have created new opportunities for deployment of wind technology on land and in regions suited for offshore development.

These trends toward improved technology, better understanding of the resource and siting issues, and falling equipment costs, suggest opportunities for continued reductions in the cost of electricity from wind. By year-end 2013, 39 states had utility-scale wind projects and all 50 states had distributed wind projects [8].[2] With growth in offshore wind in Europe and several offshore projects in advanced stages in the United States, the emergence of a U.S. offshore wind sector is also increasingly viable.

1.1.2 Electric Sector Evolution

Recent advancements in horizontal drilling and hydraulic fracturing have increased supplies of natural gas and reduced both natural gas and wholesale electricity prices. A sluggish economy from 2008 to 2013 and increased energy efficiency measures have further slowed the growth of electricity demand and reduced the need for new generation of all types. This combination of relatively inexpensive fuel and decreased need for new electric generation has reduced the demand for new wind plants.[3] Under 2013 policy conditions, these forces may cause the U.S. market for wind equipment to fall below levels that support a vibrant industry and a robust domestic wind manufacturing sector [10].

In 2013, wind generation in Iowa and South Dakota exceeded 25% of the electricity generation in those states, and seven other states procured more than 12% of their annual in-state electricity supply from wind power.

At the same time, experience with wind power in the electric sector has been rapidly evolving. In 2013, wind generation in Iowa and South Dakota exceeded 25% of the electricity generation in those states, and seven

2. Distributed wind is the use of wind turbines at homes, farms and ranches, businesses, public and industrial facilities, off-grid, and other sites connected either physically or virtually on the customer side of the meter. These turbines are used to offset all or a portion of local energy consumption at or near those locations, or are connected directly to the local grid to support grid operations. Distributed wind systems can range in size from a 1-kilowatt or smaller off-grid wind turbine at a remote cabin to a 10-kilowatt turbine at a home or agricultural load to several multi-megawatt wind turbines at a university campus, manufacturing facility, or any large energy user.

3. The increased use of flexible natural gas-fired generation, however, has helped support wind integration. For additional detail, see Chapter 2.

Table 1–1. Trends in Global Wind Capacity Additions

Year	World Annual Installations (GW)	U.S. Annual Installations (GW)	Europe Annual Installations (GW)	China Annual Installations (GW)	World Total Wind Capacity (GW)
2011	39.0	6.8	9.6	17.6	238.0
2012	45.1	13.1	12.7	13.0	283.0
2013	35.5	1.1	12.0	16.1	318.1

Sources: Global Wind Energy Council 2014 [20], International Energy Agency, IEA Wind 2013 [21]

other states procured more than 12% of their annual in-state electricity supply from wind power. Wind accounted for 4.5% of U.S. electricity end-use demand in 2013 [6], while hydropower, the most prominent renewable power source by percentage, accounted for 7.2% of the nation's electricity end-use demand [18].

As of 2013, many electric utility and power system organizations had experience operating their systems with variable wind power. Power system operators with wind supplying approximately 10% or more of their power generation through 2013 include XcelEnergy and the Electric Reliability Council of Texas [3, 4]. These and other system operators have successfully developed strategies (e.g., use of wind forecasting, broad balancing areas) to better accommodate wind's variable output characteristics [2, 3, 4, 5] and treat wind as an established part of the generating fleet (see also Chapter 2). This compares with the early 2000s, when concerns existed about potential operating costs and reliability impacts associated with the introduction of wind power into the electric system.

1.1.3 Wind Manufacturing Sector Impacts

The domestically manufactured content of wind equipment installed in the United States increased in the decade leading up to 2013, especially for large components such as blades, towers, and turbine assembly [7]. Domestic demand has been identified as a key driver of wind power manufacturing investment [19]. If local markets for new installations deteriorate, manufacturing could move from the United States to other active regions of the world, including Asia and Europe (Table 1-1).

The domestically manufactured content of wind equipment installed in the United States increased in the decade leading up to 2013, especially for large components such as blades, towers, and turbine assembly.

Growth in new manufacturing facilities, which require significant capital, is limited by policy uncertainty but remains critical to continued innovation and future cost reductions. Projected reductions in demand for new wind power installations put U.S. wind manufacturing investment in more than 560 nationwide facilities at risk. Table 1-1 compares recent U.S. installation trends with outcomes in regions with more stable policy conditions, including Europe and China.

1.1.4 Economic and Environmental Impacts

Slow economic growth in the United States and worldwide has increased policy focus on economic development. Wind projects and manufacturing bring wind-related jobs, increased tax revenues, and capital investment to local economies [22, 23, 24], as well as an array of other economic and environmental impacts as highlighted in Text Box 1-2.[4] At the same time, wind investment displaces investment in other electric generation technologies.

Public awareness has expanded to focus not only on economic conditions, but also on climate change and other environmental concerns related to electricity generation. As a result, the relative impacts on the environment from clean energy sources such as wind power are beginning to figure more prominently into decisions affecting future capacity additions.

4. Unless otherwise specified, all financial results reported in this chapter are in 2013$.

Text Box 1-2.

Economic and Environmental Benefits of U.S. Wind Power through 2013

Affordable Energy: Power Purchase Agreements for land-based wind energy negotiated from 2011–2013 averaged about $30–$40/megawatt-hour (MWh), with regional variation from about $20 to $80/MWh [7] (2013$). These costs included policy support such as the PTC.

Employment and Local Economic Benefits: By the end of 2013, approximately 50,500 individuals were employed directly in the wind equipment supply, construction, and operation sectors, with 17,400 of these in the manufacturing sector [8]. In the 39 states with utility-scale wind deployment, wind plants create permanent jobs for site operations and provide local tax and lease payments.

Domestic Manufacturing: A growing portion of the equipment used in U.S. wind power projects since 2008 has been sourced domestically [7]. According to the American Wind Energy Association, there were 560 domestic wind-related manufacturing facilities at the end of 2013 [8].

Greenhouse Gas Reductions and Fossil Fuel Displacement: Estimates indicate wind power displaced 115 million metric tonnes of carbon dioxide nationally in 2013. Major utility companies have reported fleet-wide greenhouse gas reductions and have attributed these reductions in part to existing wind capacity [25].

Reduced Water Consumption: During the Texas drought of 2011, some fossil power plants could not be operated because of shortages of cooling water. While this was occurring, the wind plants in Texas operated reliably and helped to maintain dependable electric service for customers of the Electric Reliability Council of Texas [26, 27]. National estimates indicate wind saved 36.5 billion gallons of water use within the electric power sector in 2013 [28].

1.2 Understanding the Future Potential for Wind Power

For the *Wind Vision*, economics-based electric sector modeling is used to establish a credible scenario from which costs and benefits could be calculated (Chapter 3).

This initial analysis includes a *BAU Scenario* and a series of sensitivities focused on wind costs, fossil fuel costs, and electricity demand. Analysis of wind deployment in these scenarios is conducted using the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) capacity expansion model, and is designed to inform the project team of the economic potential for wind based on changes in fundamental electric sector variables and assuming policy as of January 1, 2014.[5]

The National Renewable Energy Laboratory's ReEDS model is an electric sector capacity expansion model that calculates the competing costs of differing energy supply options and selects the most cost-effective solution. Model results are based on total system costs, including transmission, system planning, and operational requirements. ReEDS uses detailed spatial data to enable comparative electricity sector cost evaluation based on local costs and regional pricing. The model optimizes the construction and operation of electric sector assets to satisfy regional demand requirements while maintaining grid system adequacy. ReEDS uses its high spatial

5. The federal production tax credit remains expired, state renewable portfolio standards policies are as written as of January 1, 2014, and the U.S. Environmental Protection Agency's Clean Power Plan is not modeled. Pending regulatory policies, including the Cross State Air Pollution Rule, Mercury Air Toxics Standard, and others, are captured only implicitly through announced coal plant retirements.

Table 1–2. Modeling Inputs and Assumptions in *Business-as-Usual Scenario* Modeling

Modeling Variables	*BAU Scenario*	Sensitivity Variables
Electricity demand	AEO 2014 Reference Case (annual electric demand growth rate 0.7%)	1: AEO 2014 High Economic Growth Case (annual electric demand growth rate 1.5%) 2: AEO 2014 Low Economic Growth Case (annual electric demand growth rate 0.5%)
Fossil fuel prices	AEO 2014 Reference Case	1: Low Oil and Gas Resource and High Coal Cost cases (AEO 2014) 2: High Oil and Gas Resource and Low Coal Cost cases (AEO 2014)
Fossil technology and nuclear power costs	AEO 2014 Reference Case	None
Wind power costs	Median 2013 costs, with cost reductions in future years derived from literature review	1: Low costs: median 2013 costs and maximum annual cost reductions reported in literature 2: High costs: constant wind costs from 2014–2050
Other renewable power costs	Literature-based central 2013 estimate and future cost characterization	None
Policy	Policies as current and legislated on January 1, 2014	None
Transmission expansion	Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative	None

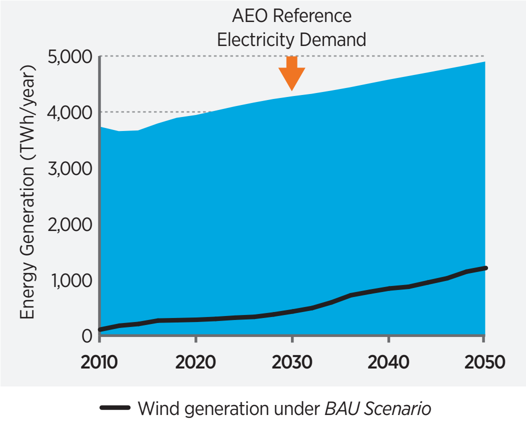
Sources: Energy Information Administration, 2014 [6], Annual Energy Outlook EIA 2014 [29], Eastern Interconnection Planning Collaborative [30].

resolution and statistical treatment of variable wind (and solar) to represent the relative value of geographically and temporally constrained renewable power sources (see Chapter 3 and Appendices G and H for further detail).[6]

The project initially explores wind deployment under the *BAU Scenario*, which is summarized in Table 1-2 (see Chapter 3 and Appendices G and H for more detail).

The results of the *BAU Scenario* analysis suggest that wind generation would serve approximately 7% of total electricity demand by 2020 once projects under construction at the end of 2013 (and qualified for the now-expired PTC) are placed into service. Minimal additional growth, up to 8% of total electricity demand, is observed by the mid-2020s. From 2015 to 2030, new wind capacity additions average 3 GW/year, less than 50% of the five-year average of approximately 7.3 GW/year achieved from 2009 to 2013. Wind installations

6. ReEDS analysis scenarios represent economically optimal futures as determined by the ReEDs decision framework. Although these scenarios are not intended to be market projections or predictions of future wind deployment, they do provide insight into the potential for wind as a function of current power sector conditions and expectations for changes in key model variables with time (e.g., fuel and technology costs). The ReEDS model originated as the Wind Deployment System, or WinDS model, which was used in the *20% Wind Energy by 2030* report. Alaska and Hawaii are excluded from the modeling analysis in this study, as ReEDS is limited to modeling the 48 contiguous states.



Historical and Average New Wind Capacity Additions Under *BAU Scenario*		
Period	GW/year	% End-Use Electricity Demand
2009–2013 (actual)	7	4.5%
2014–2020	4	7%
2021–2030	3	10%
2031–2050	8	25%

Note: The *BAU Scenario* assumes AEO Reference Case fuel costs, AEO Reference Case electricity demand, median values for renewable energy costs derived from literature, and policy as currently enacted on January 1, 2014 (i.e., no wind PTC or ITC and no assumed changes in state level RPS policies). Percentage of end-use electricity demand data are contributions as of the end of the indicated period (e.g., 2009-2013).

Figure 1-3. Wind generation and average new capacity additions under *BAU*

increase again in the late 2020s and return to levels more consistent with those prior to 2013 by the mid-2030s. Wind generation in the *BAU Scenario* is estimated at just over 1,200 terawatt-hours, or about 25% of total electricity demand in 2050 (Figure 1-3).

Starting from this initial *BAU Scenario,* a series of sensitivities is explored, evaluating changes in wind costs as well as changes in fossil fuel costs and demand. High and low wind costs are bounded by the range of projected costs drawn from the literature (see Chapter 3 and Appendix H). High and low fossil fuel costs are based on the range of projected costs in the Energy Information Administration's *Annual Energy Outlook (AEO) 2014* [29] (see Chapter 3 and Appendix G). The sensitivities consider changes in single variables relative to the *BAU Scenario,* such as wind costs, as well as changes in multiple variables, such as low wind costs and high fossil fuel costs.

Table 1-3. Wind Penetration (% Share of End-Use Demand) in the *BAU Scenario, BAU Sensitivities,* and the *Study Scenario*[7]

Year	*BAU Scenario*	***BAU* Sensitivities**			*Study Scenario*
		High Fossil Fuel Costs	Low Wind Costs	High Fossil Fuel Costs and Low Wind Costs	
2013 (actual)	4.5%	4.5%	4.5%	4.5%	**4.5%**
2020	7%	7%	8%	10%	**10%**
2030	10%	17%	16%	24%	**20%**
2050	25%	32%	34%	41%	**35%**

ReEDS analysis scenarios represent economically optimal futures as determined by the ReEDs decision framework. Although these scenarios are not intended to be market projections or predictions of future wind deployment, they do provide insight into the potential for wind as a function of current power sector conditions and expectations for changes in key model variables with time (e.g., fuel and technology costs). The ReEDS model originated as the Wind Deployment System, or WinDS model, which was used in the *20% Wind Energy by 2030* report. Alaska and Hawaii are excluded from the modeling analysis in this study, as ReEDS is limited to modeling the 48 contiguous states.

7. See Analytical Framework of the *Wind Vision* at the beginning of this chapter for a description of the scenarios analyzed.

Sensitivities with high wind costs, low fossil fuel costs, or low demand growth are observed to delay the onset of wind generation and capacity growth in the late 2020s under *BAU*, extending into the late 2030s or even the 2040s. Sensitivities that combine these variables (e.g., high wind power costs and low fossil fuel costs) result in levels of wind generation in 2050 slightly below 2013 levels, as minimal new capacity is added over the period of analysis and some existing wind capacity is retired at the end of its useful life.

Sensitivities with low wind costs, high fossil fuel costs, or high demand accelerate wind growth and drive results in wind penetration (as a share of end-use demand) to approximately 8% in 2020, 16% in 2030, and 33% in 2050. Sensitivities combining these variables (e.g., low wind costs and high fossil fuel costs) are found to support wind generation levels of 10% by 2020, 24% by 2030, and 41% by 2050 (Table 1-3).

Viewed as a whole, this analysis demonstrates that there is a broad array of potential futures for U.S. wind power. Even with a focus exclusively on wind costs and fossil fuel costs, under *BAU* conditions, wind could supply levels of generation that are essentially unchanged on the low end and in excess of 40% of total electricity demand by 2050 on the high end. Across many of the cases, wind becomes increasingly competitive with time. This occurs as wind costs continue to decline, electricity demand increases, fuel costs trend upwards, and existing power generation plants reach retirement age. These results, along with the potential for electric sector developments that are excluded from the sensitivities, indicate wind power could supply a substantial portion of future U.S. electricity needs.

1.3 Defining a Scenario for Calculating Costs, Benefits, and Other Impacts

Based on the modeling work described in this chapter, a scenario for calculating costs and benefits was selected and is referred to as the *Study Scenario.* This specific scenario is represented by a trajectory for wind generation that results in 10% of the nation's end-use demand being served by wind in 2020, 20% by 2030 and 35% by 2050.

Sensitivity analyses within the *Study Scenario* (detailed in Chapter 3) are used to assess the robustness of key results and highlight the impacts of

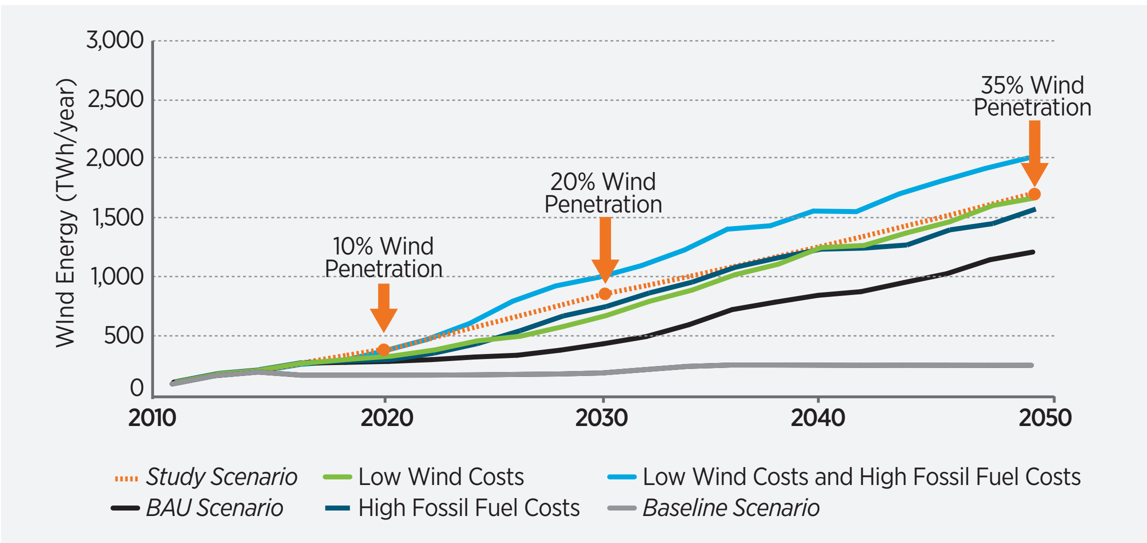
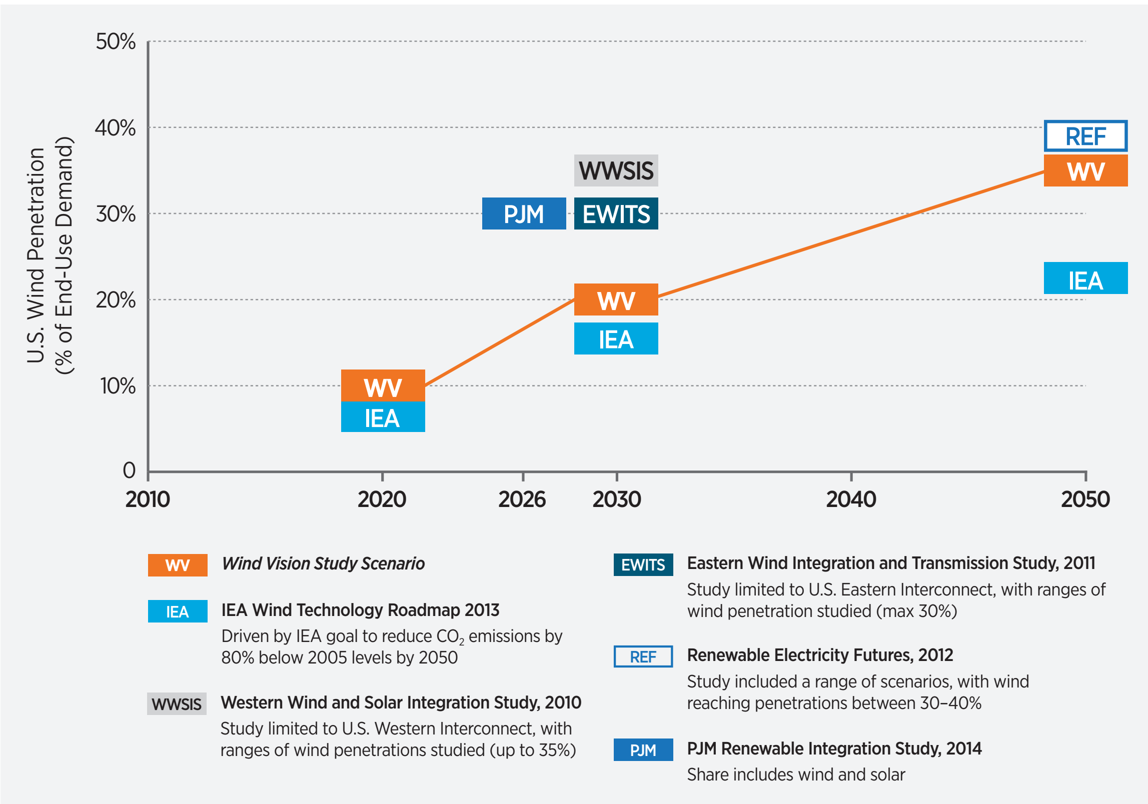


Figure 1-4. *Wind Vision Study Scenario* relative to *BAU Scenario* and Sensitivities

varying wind costs and fossil fuel costs. The *Central Study Scenario,* which is the primary case discussed here and in the Executive Summary, applies *BAU* costs and performance, fuel costs, and policy treatment, but is distinguished from *BAU* modeling by its reliance on the *Study Scenario* wind power trajectory (10% by 2020, 20% by 2030, 35% by 2050).

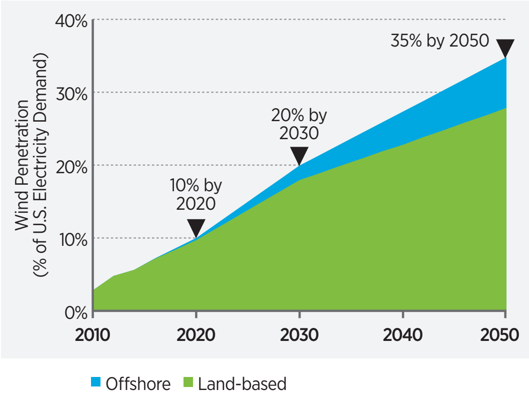
The positioning of the *Study Scenario* relative to the *BAU* results and a sub-sample of the sensitivities that entail aggressive wind cost reductions, high fossil fuel costs, or a combination of these two variables is shown in Figure 1-4. These data demonstrate that the *Study Scenario* falls within the range of outcomes indicated by economic modeling. The *Study Scenario* trajectory leverages and maintains the existing domestic industry's supply chain and manufacturing workforce, and maintains consistency with recent (i.e., 2010–2013) annual historical installations of new wind capacity.

The *Study Scenario* and the assessment of its impacts described in Chapter 3 build upon the *20% Wind Energy by 2030* report and other literature, as summarized in Figure 1-5. *Renewable Electricity Futures* [31] found wind penetration levels of 30–40% (of total end-use electricity demand) by 2050 across a series of scenarios that explored an 80% by 2050 renewable power future. A recent assessment of the literature conducted by the Intergovernmental Panel on Climate Change found median global wind penetration across carbon mitigation scenarios to be at levels of 13–14% by 2050, with a large number of scenarios (75th percentile) achieving levels of 21–25% by 2050 [32]. The International Energy Agency has estimated wind penetration levels by 2050 that limit global mean temperature increases to 2°C at 15–18% globally and 20–25% for the United States [33]. In addition, an array of power system studies has examined comparable levels of wind penetration, illustrated in Figure 1-5.[8]



Sources: International Energy Agency 2013 [33]; GE Energy 2010 [34]; Lew et al. 2013 [35]; EnerNex 2011 [36]; National Renewable Energy Laboratory 2012 [31]; Mai et al. 2014 [38]; GE Energy Consulting 2014 [39]

Figure 1–5. Wind penetration levels studied in recent literature



Cumulative Wind Capacity (GW)		2013	2020	2030	2050
Baseline Scenario	Land-based	61			
Central Study Scenario	Land-based	61	110	202	318
	Offshore	0	3	22	86
	Total	**61**	**113**	**224**	**404**

Note: Wind capacities reported here are modeled outcomes based on the *Study Scenario* percentage wind trajectory. Results assume central technology performance characteristics. Better wind plant performance would result in fewer megawatts required to achieve the specified wind percentage, while lower plant performance would require more megawatts.

Figure 1–6. The *Wind Vision Study Scenario* and *Baseline Scenario*

U.S. wind generation is based entirely on land-based technology as of 2014. The DOE recognizes, however, that offshore wind has become prominent in Europe—6.5 GW through year-end 2013 [40]—and could emerge in the United States in the near future. While the economics for offshore wind are unfavorable as of 2014, the *Study Scenario* includes an explicit allocation for offshore wind. Near-term (through 2020) offshore contributions are estimated based on projects in advanced stages of development in the United States and on global offshore wind technology innovation projections identified in the literature. Longer-term (post-2020) contributions are based on literature projections for global growth and assume continued U.S. growth in offshore (Figure 1-6). Due to quantitative modeling limitations, distributed wind applications are captured only at a qualitative level in the *Study Scenario*.

All subsequent analysis within the *Wind Vision* study is based on the *Study Scenario* trajectory and an associated scenario that provides the point of reference to calculate costs, benefits, and other impacts. This reference scenario is called the *Baseline Scenario;* it fixes installed wind capacity at year-end 2013 levels of 61 GW (Figure 1-6). Although the *Baseline Scenario* maintains wind capacity at this constant level, existing wind capacity is repowered in future years once the existing assets reach the end of their useful lives.

The *Baseline Scenario* construct allows estimates for system costs, rate impacts, land-use requirements, and transmission and integration impacts to be calculated for all future wind deployment. The benefits and impacts of large-scale wind deployment on greenhouse gas and air pollution emissions reductions, wind-supported domestic jobs, water use and withdrawal savings, air pollution impacts, and lease and property tax payments are estimated for all future wind additions. This approach highlights the degree of change within the electric power sector resulting from wind deployment specifically (e.g., new transmission needs resulting from wind deployment), as well as the incremental impact of all future wind deployment, for the purposes of understanding the economic value of wind.

While the *Study Scenario* and *Baseline Scenario* provide the wind penetration growth trajectory, a series of sensitivities on the two scenarios highlight the changes in the resulting system costs and other relevant metrics associated with changes in wind

8. Such studies include the *Western Wind and Solar Integration Study* [33, 34], the Eastern Wind Integration and Transmission Study [36], and an array of regional and transmission operator studies evaluating future renewable power scenarios summarized and reported by [37]. Although there is substantial diversity covered by the literature in this space (i.e., some studies examine the build-out of the power system, while others focus on operational characteristics given high penetration wind), analysis examining timeframes beyond 2030 often considers wind penetration levels on the order of 20% and above. The *Western Wind and Solar Integration Study* explores scenarios in which wind and solar supply up to 35% penetration by 2030 within the U.S. Western Interconnect. The *Eastern Wind Integration and Transmission Study* considers a future for the Eastern Interconnect in which wind reaches up to 30% penetration by 2030. Specific power system studies summarized by [37] focus on capacity, but also demonstrate that high penetration wind (e.g., 10–50% on a capacity basis) can be managed at costs up to $5–10/MWh.

costs and fossil fuel costs. For each variable, three sets of inputs are defined: low, central, and high. Within the sensitivity analysis, variables are altered independently (e.g., changing only the wind costs) and in combination (e.g., changing both wind costs and fossil fuel costs).

The *Wind Vision Study Scenario* is not designed to achieve any specific clean energy or carbon reduction goals. Nevertheless, the contributions of wind power in the *Study Scenario* support clean energy and carbon reduction goals. This scenario also entails a future for wind power that is consistent with broader national energy goals of grid resiliency, affordable electricity, and reduced environmental impacts including lower power sector carbon emissions.

It is possible that new disruptive concepts for converting wind power into electricity could emerge in the analysis period through 2050. Since it is difficult to predict such an occurrence, the *Wind Vision* and its *Study Scenario* do not explicitly include disruptive possibilities. The focus instead is on steady incremental optimization and continued advancement of concepts currently in use or under development. Should any major new concept emerge with potential for application at large scale, the content and results of this assessment would need to be reexamined.

1.4 Project Implementation

The *20% Wind Energy by 2030*, the *Wind Vision* study was conducted with wide-ranging participation from relevant stakeholder groups including the wind business, technology, and research communities; the electric power sector; environmental and energy-related non-governmental organizations; regulatory bodies; and government representatives at the federal and state levels. A complete listing of project participants and their contributions is in Appendix N.

DOE's Wind and Water Power Technologies Office managed the *Wind Vision* in collaboration with the American Wind Energy Association and the Wind Energy Foundation. These three organizations solicited the participation of the wind industry as well as broader stakeholders, including multiple organizations and industry sectors that view wind from a neutral perspective (including Independent System Operators, environmental stewardship organizations that evaluate wind's impacts on wildlife and the environment, other governmental organizations not related to renewable energy, and academia). Individual expert input for the project was provided by a Senior Peer Review Group comprising senior executives who represent wind, electric power, non-governmental organizations, academia, and government organizations, and who are intimately aware of wind power deployment and market issues. Overall project coordination was carried out by DOE.[9]

Eleven task forces covering the topic areas listed below conducted analyses and prepared sections of this report.

- Market Data and Analysis
- Scenario Modeling
- Wind Plant Technology
- Operations and Maintenance, Performance, and Reliability
- Manufacturing and Logistics
- Project Development and Siting
- Transmission and Integration
- Offshore Wind
- Distributed Wind
- Roadmap Development
- Communications and Outreach

Task forces each included 10–40 members, several of whom assumed primary responsibility for preparing key sections of this report. Representatives from four national laboratories—the National Renewable Energy Laboratory, Sandia National Laboratories, Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory—provided leadership and technical expertise for each of the task forces. Other task force members included representatives from the wind industry (domestic and international), academia, the electric power sector, and

9. The Office of Management and Budget's "Final Information Quality Bulletin" provides guidelines for properly managing peer review at federal agencies in compliance with section 515(a) of the Information Quality Act (Pub. L. No. 106-554). The *Wind Vision* assessment has followed these guidelines.

non-governmental organizations. In addition to the task forces, 18 peer reviewers who were not involved in the writing or analysis reviewed the report content for accuracy and objectivity.

Various offices within DOE and other federal agencies also provided counsel and review throughout the effort. DOE's Office of Energy Efficiency and Renewable Energy was a principal internal adviser. DOE's Office of Energy Policy and Systems Analysis also provided guidance. Consultations were conducted with other DOE energy programs, including solar, geothermal, and water (hydro-electric), to obtain the best available information on characteristics for those technologies. Coordination was also established with other federal agencies, such as the U.S. Department of the Interior's Bureau of Ocean Energy Management, U.S. Environmental Protection Agency, Federal Energy Regulatory Commission, and the National Oceanic and Atmospheric Administration.

The *Wind Vision* research and analysis began in spring 2013 concluding with the report's publication in spring 2015. Data and methods that were publicly available through year-end 2013 were used to develop modeling inputs, benefits analyses, and documentation of the state of wind power. The majority of the report findings are reported in 2013$ except where otherwise noted. Because the writing, peer review, and editing of the report occurred in 2014, data sources and market or policy developments occurring in 2014 or later may not be fully reflected in the report's materials.

1.5 Report Organization

The *Wind Vision* examines the prospective contributions, impacts, and value offered by wind power as part of a diverse future low carbon electricity portfolio, and presents an updated scenario for wind expansion in 2020, 2030, and 2050. This introductory chapter is followed by three additional chapters and a series of appendices. Chapter 2 discusses the status of the wind industry, describing historic progress, relevant conditions as of 2013, and emerging trends. Chapter 3 describes the *Wind Vision* analysis and modeling results and provides a detailed discussion of the impacts associated with the *Study Scenario,* including expected costs and benefits. Chapter 4 identifies technical, economic, and institutional actions that could support achievement of the *Study Scenario*.

The appendices provide additional background and detail developed by the expert task forces:

- **Appendix A** is a glossary that contains definitions of frequently used terms in the report.
- **Appendix B** is a summary of the prior DOE report *20% Wind Energy by 2030.*
- **Appendix C** is a discussion of regulatory agencies and permitting processes affecting U.S. wind projects.
- **Appendix D** contains information on the costs and timeline for project permitting in 2014, providing further detail to topics discussed in Chapter 2.
- **Appendix E** contains information on the domestic supply chain capacity, providing further detail to topics discussed in Chapter 2.
- **Appendix F** contains information on testing facilities, providing further detail to topics discussed in Chapter 2.
- **Appendix G** contains additional, non-wind inputs and assumptions used for the ReEDS scenario modeling.
- **Appendix H** details the wind cost inputs and assumptions used for the ReEDS scenario modeling.
- **Appendix I** is a more detailed review of the Jobs and Economic Development Impacts Model (known as JEDI) used to quantify job impacts of the *Study Scenario*.
- **Appendix J** provides further details on the methods used to estimate greenhouse gas reductions of the *Study Scenario.*
- **Appendix K** provides further results from the analysis of the water impacts of the *Study Scenario.*
- **Appendix L** provides further details regarding the methods used to quantify the air pollution impacts of the *Study Scenario*.
- **Appendix M** provides detailed *Wind Vision* roadmap actions for relevant sectors, expanding upon material presented in Chapter 4.
- **Appendix N** lists the individuals who contributed to this project.
- **Appendix O** describes the impacts of higher turbine heights on the regional deployment of wind—including technology, marketing and permitting challenges.

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2 Wind Power in the United States:

Recent Progress, Status Today, and Emerging Trends

Summary

With more than 61 gigawatts (GW) installed across 39 states at the end of 2013, wind power has confirmed its credibility as a scalable, reliable and environmentally sound energy technology, and a cost-effective source of low emissions power generation in those regions of the United States in which substantial wind potential exists. The United States has more than 15,000 GW of technical[1] wind resource potential, both land-based and offshore, that can be harnessed and delivered reliably into existing power networks through utility-scale and distributed installations [1]. U.S. wind generation was entirely land-based technology as of 2013. The U.S. Department of Energy (DOE) recognizes, however, that offshore wind has become prominent in Europe—reaching 6.5 GW through year-end 2013 [2]—and could emerge in the United States in the near future. Nearly all scales of wind power technology are reflected in the *Wind Vision* study,[2] although distributed wind applications are captured primarily within the larger land-based designation.[3] In this chapter, offshore and distributed wind technologies are highlighted in Sections 2.2 and 2.3, respectively.

U.S. electricity demand served by wind power has tripled since 2008, increasing from 1.5% of total end-use demand to 4.5%[4] in 2013 [3]. Trends indicate that continued and increased wind deployment can have significant and wide-ranging positive effects for the nation's energy mix and environmental goals, while at the same time creating jobs and economic development activities associated with wind deployment and equipment manufacturing. These resources and trends—combined with cost reductions, technology advances, increased industry collaboration, and improved reliability—provide the foundation for the *Wind Vision Study Scenario,* introduced in Chapter 1 and summarized in Chapter 3, Text Box 3-2.

Wind power has become an established, reliable contributor to the nation's electricity supply. It provides affordable, clean domestic energy as part of a portfolio of sustainable power generation options.

Wind technology improvements have evolved to make lower wind speed sites[5] more economically viable even in regions previously thought to have limited wind potential, such as the Southeast. Despite deployment growth, technology enhancements, and cost reductions, however, wind power expansion continues to be affected by energy demand, transmission and integration limitations, fluctuations in raw material costs, policy uncertainty, conflicting uses, siting concerns, and competition with other energy sources such as natural gas.

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1. The National Renewable Energy Laboratory (NREL) routinely estimates the technical potential of specific renewable electricity generation technologies. These are technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed. *www.nrel.gov*
2. Wind turbines can range in sizes from small 1 kW machines to multi-MW offshore turbines. The *Wind Vision* primarily focuses on centralized power generation that utilizes utility-scale (1MW+) land-based and offshore wind turbines.
3. Distributed wind is the use of wind turbines at homes, farms and ranches, businesses, public and industrial facilities, off-grid, and other sites connected either physically or virtually on the customer side of the meter. These turbines are used to offset all or a portion of local energy consumption at or near those locations, or are connected directly to the local grid to support grid operations. Distributed wind systems can range in size from a 1-kilowatt or smaller off-grid wind turbine at a remote cabin to a 10-kilowatt turbine at a home or agricultural load to several multi-megawatt wind turbines at a university campus, manufacturing facility, or any large energy user.
4. The *Wind Vision* metric for the share of wind in a given year is calculated using data published by the EIA, as total net wind generation divided by total annual electricity retail sales. This ratio is 4.5% for 2013 and is consistent with the definitions for the future wind penetration levels in the *Wind Vision Study Scenario* as noted in Chapter 1.
5. In *Wind Vision*, 'lower wind speed sites' are those with average wind speeds less than 7.5 meters per second [m/s] at hub height. In the International Electrotechnical Commission (IEC) turbine classification system this is equivalent to IEC Class 3 or higher turbine class.

2.0 Introduction

This chapter summarizes the state of wind power as of year-end 2013 across a number of aspects, including wind power markets and economics; economic and social impacts, including workforce development and environmental effects; wind resource characterization; wind technology and performance; supply chain, manufacturing, and logistics; wind integration and delivery; wind siting, permitting, and deployment; and collaboration, education, and outreach. More recent data for 2014 may be available but were excluded due to publication schedule requirements. The special issues surrounding offshore wind and distributed wind are also presented. This compilation characterizes the trends influencing formation of the *Wind Vision Study Scenario* (Chapter 3) and aligns them to roadmap activities described in Chapter 4. The following is a short summary of key points in this chapter.

Wind Power Markets and Economics

Investments in wind manufacturing and deployment continue to support industry growth. According to the United Nations Environment Programme, global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21% [4, 5].[6] Domestic manufacturing for many wind components is strong largely because of this investment trend, technical advancements that have helped make wind viable even in lower resource areas, and increased domestic demand for wind power. The combined import share of selected wind equipment tracked by trade codes (i.e., blades, towers, generators, gearboxes, and complete nacelles), when presented as a fraction of total equipment-related turbine costs, declined from roughly 80% in 2006–2007 to 30% in 2012–2013 [6]. The share of wind turbine project costs, including non-turbine equipment project costs that were sourced domestically, was approximately 60% in 2012 [6]. In 2013, the wind supply chain included more than 560 facilities across 43 states [7]. Given the transport and logistics challenges of moving large wind turbine components over long distances, continued U.S. manufacturing and supply chain vitality is expected to be at least partially coupled to future levels of domestic demand for wind equipment. Recent fluctuations in demand and market uncertainty have forced some manufacturing facilities to furlough employees and others to cease operations altogether.

The levelized cost of electricity (LCOE) is the present value of total costs incurred to deliver electricity to the point of grid connection, divided by the present value of energy production over a defined duration. In effect, LCOE is the cost of generating electricity from a specific source—over an assumed financial lifetime—that allows recovery of all project expenses and meets investor return requirements. LCOE provides an economic assessment of the cost of the energy-generating system including all costs over its lifetime: initial investment, operations, and maintenance; cost of fuel; and cost of capital.

In sites with higher wind speeds,[7] the LCOE of wind declined by more than 33% from 2009–2013, and, in some markets, wind power sales prices are competitive with traditional fossil generation [6]. Significant variations, however, are seen in the LCOE of individual wind projects. The LCOE for wind is influenced by capital and balance of system costs, operations and maintenance (O&M) costs, financing costs, and project performance. Incentives and policies also have significant effects on project-specific LCOE, most notably for wind project development costs and power purchase agreement (PPA) terms.

Installation rates for wind projects are affected by overall electricity demand, wholesale power prices, and state and federal policies. A national boom in natural gas reserves has created some uncertainties for wind power in the near term. The Energy Information Administration (EIA) confirmed 29% of the nation's electric power as coming from natural gas in 2012. This trend fell to 26% in 2013, but natural gas still exerted downward pressure on wholesale power prices. At the same time, overall energy demand since 2008 has remained constant due to a stagnant economy coupled with energy efficiency improvements—thus reducing overall growth for electricity generation technologies, including wind.

6. Unless otherwise specified, all financial results reported in this chapter are in 2013$.

7. In the *Wind Vision,* 'higher wind speed sites' are those with average wind speeds of 7.5 meters per second [m/s] or higher at hub height. In the International Electrotechnical Commission (IEC) turbine classification system this is equivalent to IEC Class 2 or 1 turbine classes.

Economic and Social Impacts

Operating experience and research demonstrate that the current and potential social benefits of wind power are wide-ranging and significant. For example, a 2012 study evaluating county-level economic development effects in counties with wind development determined that wind power installations between 2000 and 2008 increased county-level personal income by approximately $11,000 for every megawatt (MW) of installed capacity [8]. These estimates translate to a median increase in total county personal income and employment of 0.2% and 0.4% for counties with installed wind power over the same period. Similarly, a 2011 study in four rural counties in western Texas found total economic activity in local communities to be nearly $730 million over the assumed 20-year life cycle of the plants, or $520,000 (2011$) per MW of installed capacity. These economic benefits derive from increased personal income and reduced electric rates; temporary and permanent employment in construction, engineering, transportation, manufacturing, and operations; local economic activity resulting from wind construction; and increased revenues from land lease payments and tax revenue. Nationally, wind power projects delivered at least $180 million annually to local landowners through lease payments in 2013 [9].

In addition to significant economic and employment-related benefits, wind deployment also offers health and environmental benefits including reduced greenhouse gas (GHG) emissions; reduced harmful air pollutants such as sulfur dioxide (SO_2), nitrogen oxide (NO_x), and particle matter; and reduced water use. Wind power in the United States in 2013 was estimated to have reduced direct power-sector carbon dioxide (CO_2) emissions by 115 million metric tonnes (127 million short tons), equivalent to eliminating the emissions of 20 million cars during the year. An estimated 157,000 metric tonnes (173,000 short tons) of SO_2 emissions and 97,000 metric tonnes (107,000 short tons) of NO_x were avoided due to the wind power generated in 2013. Wind power generation in 2013 is estimated to have reduced power-sector water consumption by 36.5 billion gallons, or roughly 116 gallons per person in the United States [10].

Wind Technology and Performance, Supply Chain, Manufacturing, and Logistics

Continued advancements in land-based turbines and offshore wind technologies enhance wind power opportunities in every geographic region of the United States. Progress has been made to improve performance and reliability and reduce the cost of individual wind turbines. Enhancements have included design of longer blades and taller towers that capture more energy from the wind, developments in drive train designs, and use of improved controls and sensors. By 2013, focus began shifting from individual turbine performance to overall system performance characteristics.

Technology advancements center on developing enhanced micro-siting strategies and complex control systems for arrays of wind turbines. These enhanced technologies broaden the range of viable wind sites by facilitating greater energy capture at high wind speeds as well as economical energy capture at lower wind speeds. A better understanding of the wind resource and continued technology developments are leading trends in improved performance, increased reliability, and reduced cost of wind electricity. Additionally, declining wind power costs are driving domestic demand for wind power, wind industry jobs, and economic growth in all regions of the country. As turbine multi-MW wind technology advances and components like blades and towers increase in size, however, transportation costs could increase and manufacturing may become more complex.

Based on installation experience gained between 2006 and 2013, expanded domestic manufacturing will not be constrained by raw materials availability or manufacturing capability. Reductions in demand for wind power, however, will channel resources to other industries and could slow a return to high levels of wind deployment [11]. Equipment and skilled labor availability will continue to be dependent on near-term domestic demand. Continued innovation in turbine design, manufacturing, transportation, and construction can help the industry overcome logistical barriers and improve international competitiveness.

Wind Integration and Delivery

Wind power has become a major contributor to electricity supply in the nation and around the world. U.S. electric power networks have operated reliably with high wind contributions of 10% and higher on an annual basis, with minimal impacts on network operating costs. Power system operators experienced with wind now view wind generation routinely as a dependable component of their portfolio of generating options. Nine U.S. states are currently operating with greater than 12% of their annual electricity generation from wind (Colorado, Idaho, Iowa, Kansas, Minnesota, North Dakota, Oklahoma, Oregon, and South Dakota), with two of them (Iowa and South Dakota) operating with greater than 25% of in-state generation from wind [7].

Large amounts of wind have been and continue to be reliably and effectively integrated into electric power systems, but many sites with wind power resources have minimal or no access to electrical transmission facilities. This hurdle is a bottleneck to cost-effective wind deployment, and additional transmission system expansion is needed for higher wind penetration levels [9]. Concerted effort has yielded progress nationally in addressing transmission and interconnection barriers, and curtailment[8] has been reduced from its peak in 2009 [6]. Siting, planning, and cost-allocation issues remain barriers to transmission investment for wind and other forms of generation, but dedicated efforts continue to yield progress in addressing these concerns.

Wind turbine technology has evolved to incorporate more direct drive technology, which has been relatively slow to enter the U.S. market features. New grid-friendly features have evolved, such as low-voltage ride-through. This feature allows wind turbines to stay online during low-voltage events, contributing to system stability. In addition, frequency response—the ability of the wind turbine to increase or decrease generation to help support nominal system frequency of 60 Hertz—is now a feature of modern wind turbines. The ability to respond to automatic generator control signals, or AGC, allows wind turbines to provide regulation service—system balancing on very short time scales from about 4 seconds to several minutes, depending on the region. Finally, simulated inertial response provides fast response during a disturbance.

Wind Siting, Permitting, Deployment, and Collaboration

As of 2013, both the processes and information requirements for permitting wind projects vary across applications (land-based, offshore, and distributed) as well as across geographic boundaries (locate, state and federal). This lack of uniformity in the regulatory environment can lead to uncertainties in project development timelines and success.

Industry experience and research have improved understanding of wind power's impacts to wildlife and local communities. Progress has been made through careful siting, public engagement, and mitigation strategies. While improvements have been made with respect to understanding impacts and identifying effective mitigation strategies, however, continued research is needed to further understand the true nature and extent of wildlife impacts. The focus is on co-existence—addressing community and regulatory concerns while maximizing wind power opportunities. Open collaboration with the community and its leaders increases public involvement and comprehension about best practices to manage social impacts for both offshore and land-based wind developments. Offshore wind is still in early development phases, but significant progress is being made to facilitate siting, leasing, and construction of offshore wind power projects in both federal and state waters.

A number of government agencies, industry organizations, researchers and academia, non-government organizations (NGOs), and collaborative groups such as the American Wind Wildlife Institute, Bats and Wind Energy Cooperative, National Wind Coordinating Collaborative, and the Utility Variable-Generation Integration Group are working to address wind-related issues ranging from permitting and environmental oversight to manufacturing, workforce training, and facilitation of electric power system integration. These organizations have furthered scientific understanding to help stakeholders realize the role and impact of wind on the energy market, communities, and the environment. Work by collaborative groups has shifted from the basic sharing of information and best practices to active engagement aimed at solving specific problems.

8. Curtailment refers to wind energy available but not used due to transmission constraints and/or system inflexibility.

2.1 Wind Power Markets and Economics

Wind was first used to generate electricity in Scotland in 1887 and was introduced in the United States in 1888 [12]. It was not until nearly a century later, however, that technological research and development—spurred in part by the oil crisis of the 1970s—led to the installation of significant amounts of utility-scale wind power globally and in the United States. From the mid-1980s to the late 1990s, wind began gaining traction in the electric sector.

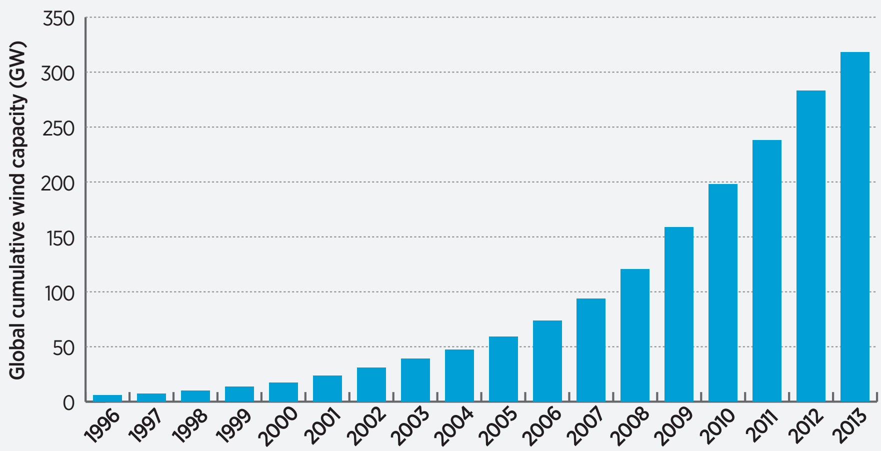
Wind power is cost effective and reliable. Wind power capacity, generation, and investment have grown dramatically.

This section provides insight into various topics related to the wind market. Current global market trends and domestic market trends are summarized in Sections 2.1.1 and 2.1.2. Domestic cost and pricing trends, including cost of energy, PPAs, capital cost, O&M costs, project financing, and project performance are discussed in Section 2.1.3. Section 2.1.4 summarizes U.S. electricity supply and demand issues, including electricity load, natural gas prices, and power plant retirements. Section 2.1.5 discusses market drivers and policy, and covers such topics as federal and state policy for wind, policy uncertainty, and incremental growth trends.

2.1.1 Global Market Trends

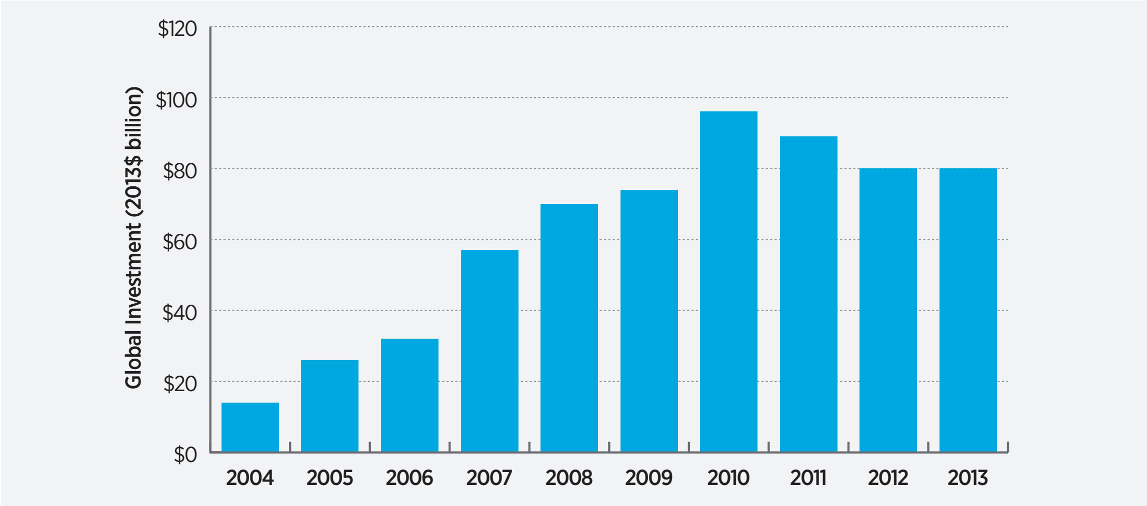
Globally, wind power capacity, generation, and investment have grown dramatically since the late 1990s. Cumulative global installed wind power capacity grew from just 6 GW at the end of 1996 to 318 GW at the end of 2013 (Figure 2-1) [13]. Approximately 3% of global electricity supply came from wind in 2013 [6, 14], up from 0.9% in 2007 [15]. As part of this total, global offshore wind capacity has grown from less than 100 MW in 2000 to nearly 7 GW at the end of 2013 [14]. This capacity is installed mainly in Europe, with a small amount installed in Asia.

According to the United Nations Environment Programme, global investment in wind power grew from $14 billion in 2004 to $80 billion in 2013, a compound annual growth rate of 21% (Figure 2-2) [4, 5]. Wind power represented more than one-third of the total $214 billion invested globally in renewable energy in 2013. Annual investment in wind reached a record high in 2010 at $96 billion, and dropped from 2011 to 2013 due in part to global economic trends as well as falling wind project capital costs. Total wind investment over the decade 2004–2013 was more than $600 billion. An estimated 834,000 global direct and indirect jobs were tied to wind power in 2013 [16].



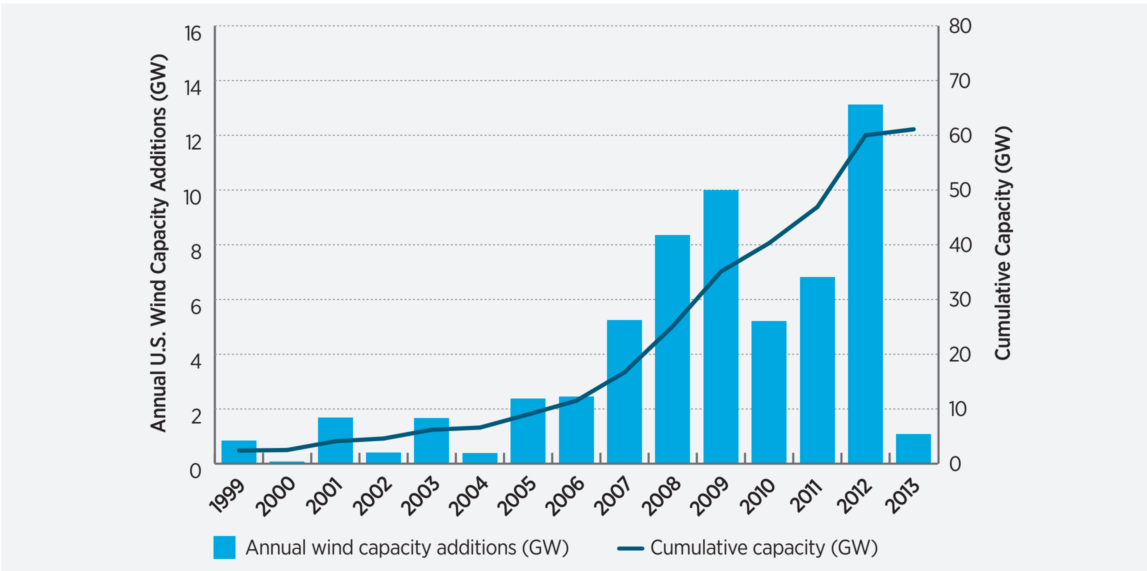
Source: Adapted from the GWEC [13]

Figure 2-1. Global cumulative installed wind capacity, 1996–2013



Source: Adapted from UNEP [5]

Figure 2-2. Global trends in wind power investment, 2004–2013



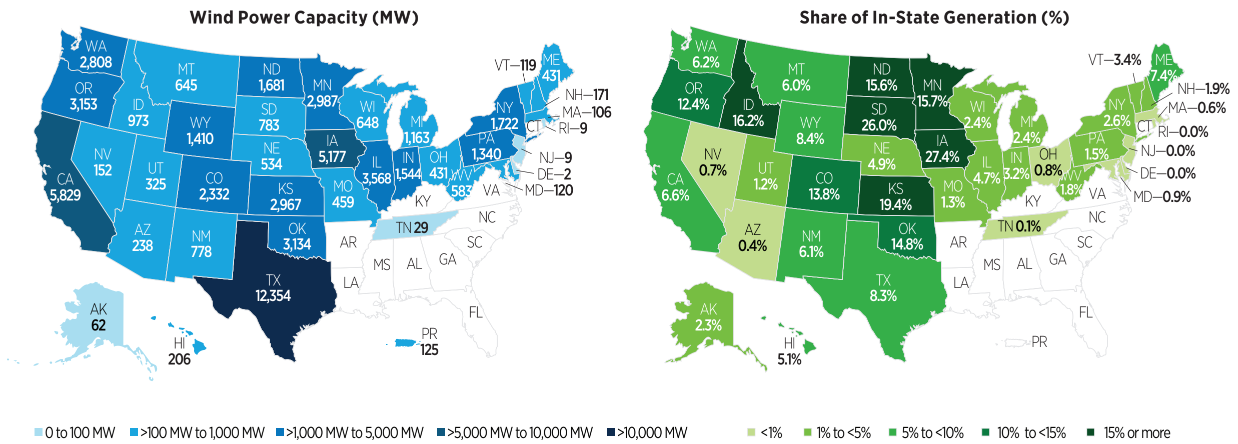
Source: Adapted from AWEA 2014 [7]

Figure 2-3. U.S. installed wind capacity, 1999–2013

2.1.2 Domestic Market Trends

Wind power is an important contributor to domestic power generation in the United States, with cumulative installed wind capacity growing from 1.4 GW in 1996 to 61 GW in 2013 (Figure 2-3) [7, 17]. The *output of electricity* from this wind capacity grew from 3.2 terawatt-hours to 168 terawatt-hours over the same period. This output was equal to 4.5% of national end-use demand (for electricity) in 2013—enough to power 15.5 million U.S. residences [3, 17].

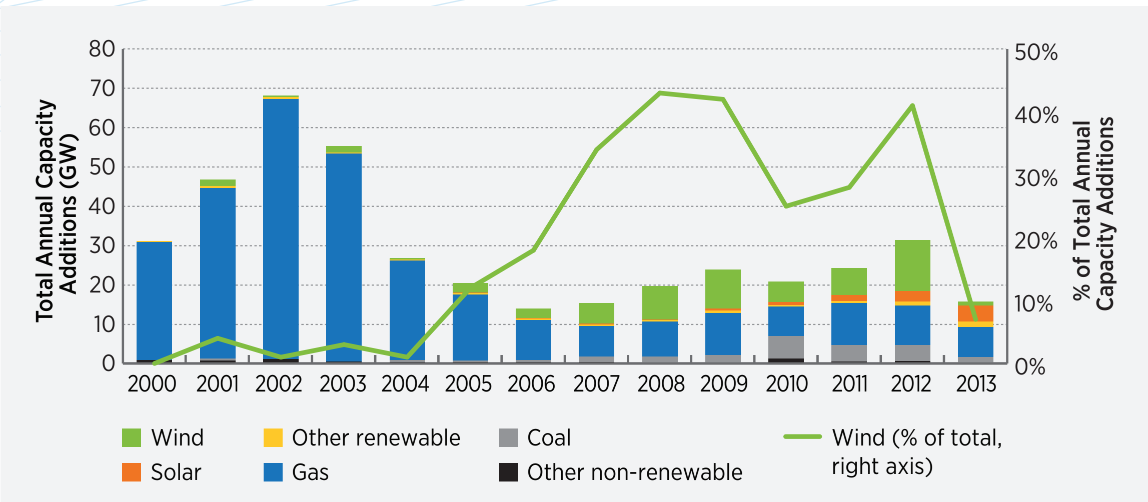
The geographic spread of wind project development in the United States is broad (Figure 2-4). In 2013, nine U.S. states generated more than 12% of their in-state electricity from wind. The top producers were Iowa at 27.4% and South Dakota at 26% [7].



Source: AWEA [7]

Figure 2-4. U.S. utility-scale wind power capacity and share of in-state generation, year-end 2013

Wind power constituted an average of 34% of the total new generating capacity added in the United States each year from 2007 to 2013 [6] (Figure 2-5). The 13 GW of wind installed in 2012 surpassed natural gas to comprise the greatest annual addition of any technology in that year [6]. Wind capacity additions dropped 92% in 2013, however, with only 1.1 GW added representing just 7% of total generating capacity additions [7]. Two key factors contributed to the meager growth in 2013. The first was record growth in 2012 as developers focused on completing projects in advance of the then-planned expiration of federal tax incentives for wind. The second was limited motivation to achieve commercial operations by year-end 2013. This was the result of altered tax incentive eligibility guidelines that, after federal tax incentives were extended, only required construction to have begun by the end of the year. Wind capacity additions in 2013 represented less than $2 billion of investment, down from $25 billion in 2012 [6]. Construction started on a significant number of wind projects in 2013, as developers sought to take advantage of federal tax incentives for projects that initiated construction by year-end. Those projects will come online in 2014 and 2015.



Source: Wiser and Bolinger [6]

Figure 2-5. Relative contribution of generation types in U.S. capacity additions, 2000–2013

Text Box 2-1.

Domestic Market Trends

When *20% Wind Energy* by 2030 was published in 2008, numerous Fortune 100 companies had begun purchasing renewable energy certificates to fulfill corporate sustainability goals concerning energy and greenhouse gas emissions. Renewable energy certificates provide firms the environmental attributes associated with renewable energy without physically changing the firm's electricity supply or providers. Since 2008, corporate purchasing interest has expanded beyond renewable energy certificates into direct power purchase agreements and even on-site direct investment in wind power, indicating long-term corporate commitment to renewable power. By 2012, 59% of Fortune 100 firms had GHG emission reduction commitments, renewable energy commitments, or both [19].

Some recent examples of corporate investment in wind power are noted below:

- By year end 2014, Google had signed 1,040 megawatts (MW) worth of long-term wind contracts, including several 20-year power purchase agreements contracts. These power purchase agreements will power their Iowa, Texas and Oklahoma data centers [20]. Another notable corporate power purchase agreements purchase included Microsoft's agreement to purchase all the electricity from a 175 MW wind plant to supply their Illinois data center [7].
- IKEA Group purchased 2 U.S. wind plants in 2014 [21a, 21b], which together will supply IKEA nearly 1,000 GWh/year of wind energy. IKEA is a full owner of these assets, with Apex Clean Energy operating the plants.
- In 2014, Intel Corporation, Staples, and Unilever were supplied 100% by green power through a combination of solar, wind, and biomass technologies. All three firms fulfilled their renewables portfolio through a mix of on-site generation, renewable energy certificates, and power purchase agreements [20].
- Wal-Mart has a goal of operating with 100% renewable energy by 2020 through a mix of PPAs, on-site generation, and renewable energy certificates. In 2012 Wal-Mart installed its first onsite utility-scale wind turbine at a California distribution center. Wal-Mart also has small wind turbines operating at a Massachusetts store as well as numerous facilities with roof-top solar.

Despite tepid growth in 2013, annual and cumulative wind power installations in the United States have exceeded the early-year pathway (through 2013) in DOE's *20% Wind Energy by 2030* report [18]. This demonstrates that wind can deploy rapidly, as is consistent with high penetration scenarios.

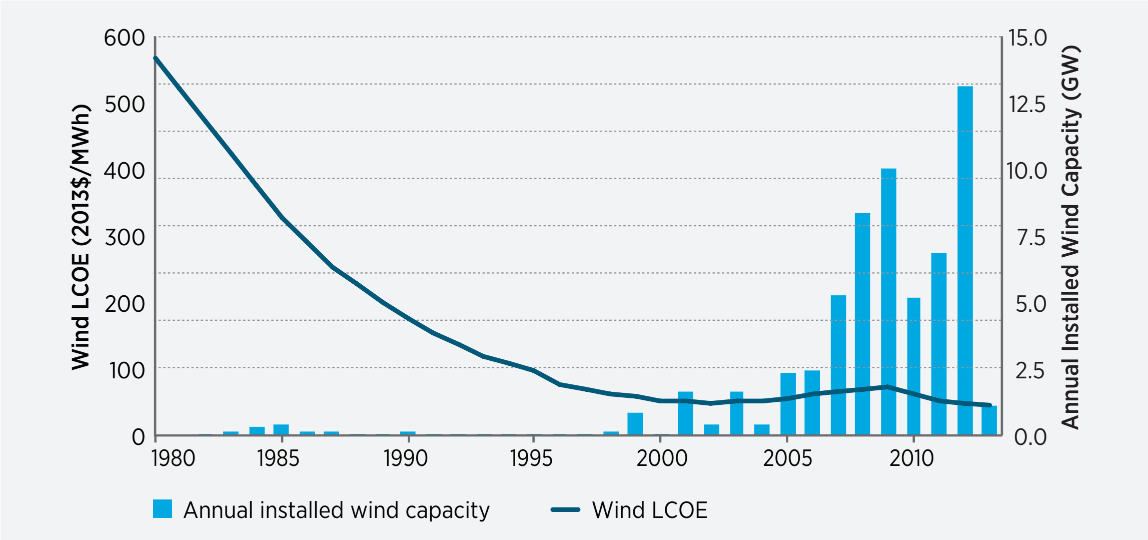
2.1.3 Domestic Cost and Pricing Trends

In sites with higher wind speeds, the LCOE of wind dropped by more than one-third over the five-year period from 2009 to 2013 [6]. In some regional wind markets,[9] wind is competitive with traditional fossil generation [6]. Trends in the cost of wind power and the related prices negotiated in PPAs impact wind power deployment. The LCOE of wind, in turn, is influenced by trends in wind project capital costs; ongoing O&M costs; project financing terms; and project performance.

Cost of Energy

Through technology advancement and turbine scale-up, the average LCOE for U.S. land-based wind projects in good to excellent sites dropped more than 90% from 1980 to 2013—that is, from more than $0.50/kilowatt-hour (kWh) in 1980 to just $0.045/kWh in 2013, excluding the federal production tax

9. The strength of a regional market is determined by a combination of factors, including the natural wind resources, access to transmission, policy incentives and regulatory conditions, and the region's level of historical experience in wind power.



Note: In the *Wind Vision,* 'good to excellent sites' are those with average wind speeds of 7.5 meters per second (m/s) or higher at hub height. LCOE estimates exclude the PTC.

Source: Adapted from Lawrence Berkeley National Laboratory 2014 data [23]

Figure 2-6. Average LCOE in good to excellent wind sites

credit (PTC) [6] (Figure 2-6). Significant variations exist in the LCOE of individual wind projects, however, and projects in lower wind resource sites have higher LCOE. On average, after experiencing an increase beginning in 2003 and peaking in 2009, the LCOE of wind in good to excellent sites[10] dropped by more than one-third over the five-year period from 2008 to 2013. These cost reductions were supported by many factors, including technology advancement, turbine scale-up, and efficiencies gained from larger volume manufacturing.

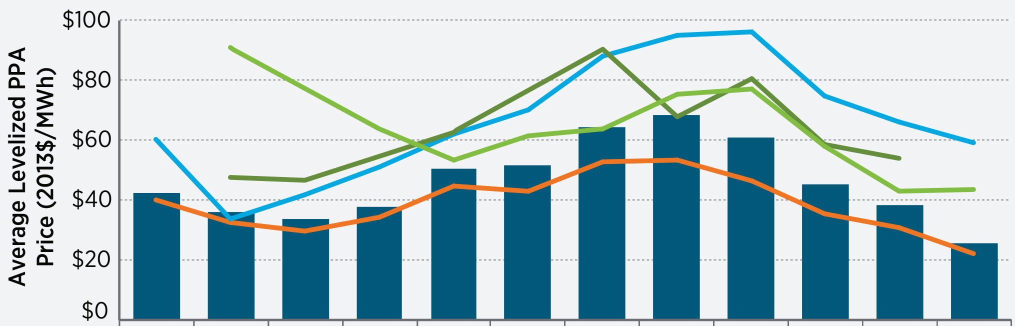
Power Purchase Agreements

Wind PPA prices represent the cost paid by electric utilities for wind power under long-term contracts. Such prices are impacted by the LCOE of wind projects as well as the available federal and state incentives. Average land-based wind PPA prices for a sample of national and regional U.S. wind projects are shown in Figure 2-7. As a result of trends in LCOE and support via federal tax incentives, wind power is now cost-effective in many regions of the United States despite historically low wholesale power prices.

Despite increasing from 2003 to 2009 (Figure 2-7), average wind PPA prices remained competitive with rising wholesale power prices over much of this period [6]. This alignment helped support dramatic growth in wind power additions. Declining wholesale power prices since 2008 have challenged wind economics, but a simultaneous reduction in wind PPA pricing has kept wind competitive in some regions, especially the U.S. Interior [6]. In part as a result of the decline in wind PPA pricing, in 2012 more than 11 GW of wind power capacity was installed in states without any near-term incremental demand from state renewable portfolio standards (RPSs) [22]. In 2013, the national average PPA price for contracts signed was approximately $25/megawatt-hour (MWh) including the PTC, which is a $15/MWh reduction from the 2012 generation weighted average [24]. The Interior region of the United States has the lowest PPA prices, largely because it has the best wind resources in the nation.[11] While the wind resource quality in other regions is not expected to change with time, cost improvements gained from wind power experience and advancements in infrastructure, siting, and permitting may help lower PPA prices in these regions in the future.

10. Defined here to include wind projects built in the interior of the country, where some of the nation's most consistent wind resources exist.

11 High quality wind resources are characterized by consistent, predictable high wind speeds.



PPA Year:	1996-99	2000-01	2002-03	2004-05	2006	2007	2008	2009	2010	2011	2012	2013
Contracts:	10	17	24	30	30	26	39	49	48	38	13	18
MW:	553	1,249	1,382	2,190	2,311	1,781	3,465	4,048	4,642	3,980	970	2,761

Nationwide | Interior | West | Northeast | Great Lakes

Note: The Interior region includes Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, Wyoming, Colorado, and New Mexico. The West region includes Washington, Oregon, Idaho, California, Nevada, Utah, and Arizona. The Northeast region includes Maine, Vermont, New Hampshire, Connecticut, New York, Massachusetts, Rhode Island, Pennsylvania, and New Jersey. The Great Lakes region includes Ohio, Indiana, Illinois, Michigan, and Wisconsin.

Source: Wiser and Bolinger [6]

Figure 2-7. Generation-weighted average, levelized wind PPA prices by PPA execution date and region

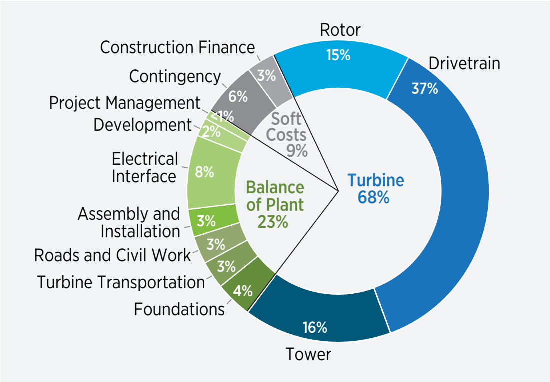
Capital Cost

The capital cost of land-based wind projects has affected trends in wind power LCOE and PPA pricing. Average *wind turbine* prices reached a low of roughly $750/kilowatt (kW) between 2000 and 2002, but then increased between 2004 and 2009 to roughly $1,500/kW—a trend attributed to weakness in the U.S. dollar; rising labor costs, profit margins, and warranty provisions among turbine manufacturers; and increasing raw materials and energy prices [25, 26]. A subsequent reversal of some of these underlying trends, as well as increased competition among manufacturers, led to a significant decrease in turbine prices since 2009. For the most recent (as of 2013) contracts, Bloomberg reports global average pricing of approximately $1,000/kW for older turbine models and $1,300/kW for newer turbine models that feature larger rotors [27].

Total installed *project* capital costs include not only the turbine, but also the balance of system (BOS) costs. BOS costs comprise balance of plant[12] and "soft" costs[13] [28] (Figure 2-8). As shown in Figure 2-9, installed project costs dropped from roughly $5,000/kW in the early 1980s to a low of approximately $1,300/kW in 2004. Similar to turbine costs, project capital costs then increased through 2009 before dropping again. In 2013, the average installed project cost was roughly $1,630/kW, down more than $300/kW from the reported average cost in 2012 and more than $600/kW less than the apparent peak in average reported costs in 2009 and 2010 [6]. With just 11 projects totaling 650 MW, however, the 2013 sample size is limited, which may mean a few large and low-cost projects are unduly influencing the weighted average. Early indications from a larger sample of projects under construction in 2014 (16 projects totaling more than 2 GW) suggest that average installed costs are closer to $1,750/kW—still down significantly from 2012 levels [6].

12. Balance of plant refers to infrastructure elements of a wind plant other than the turbines, e.g., substation hardware, cabling, wiring, access roads, and crane pads.

13. Soft costs are non-infrastructure costs associated with a wind plant, e.g., project development and permitting.



Source: Tegen et al. [28]

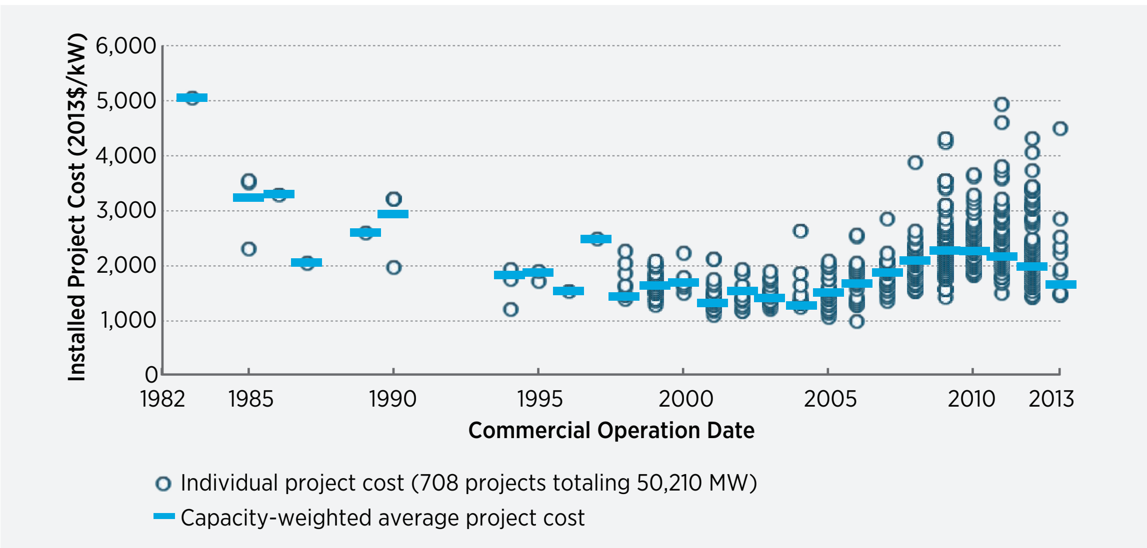
Figure 2-8. Components of installed capital cost for a land-based, utility-scale reference wind turbine

O&M Costs

O&M costs are an important component of the overall cost of wind power and can vary substantially among projects. Anecdotal evidence and analysis suggest that unscheduled maintenance and premature component failure in particular challenge the wind power industry [29]. While O&M cost allocation and categorization is not consistent across the industry, a recent report found U.S. wind O&M costs comprise scheduled maintenance (20.5%), unscheduled maintenance (47.7%), and balance of system (31.9%) [30].

Though market data on actual project-level O&M costs are not widely available, some overall cost trends can be discerned. First, as noted, O&M costs generally increase as projects age [25]. Second, trends by project vintage are unclear, with some analysis suggesting increasing costs in recent years (to 2014) and other analysis suggesting the opposite [25, 29, 31].

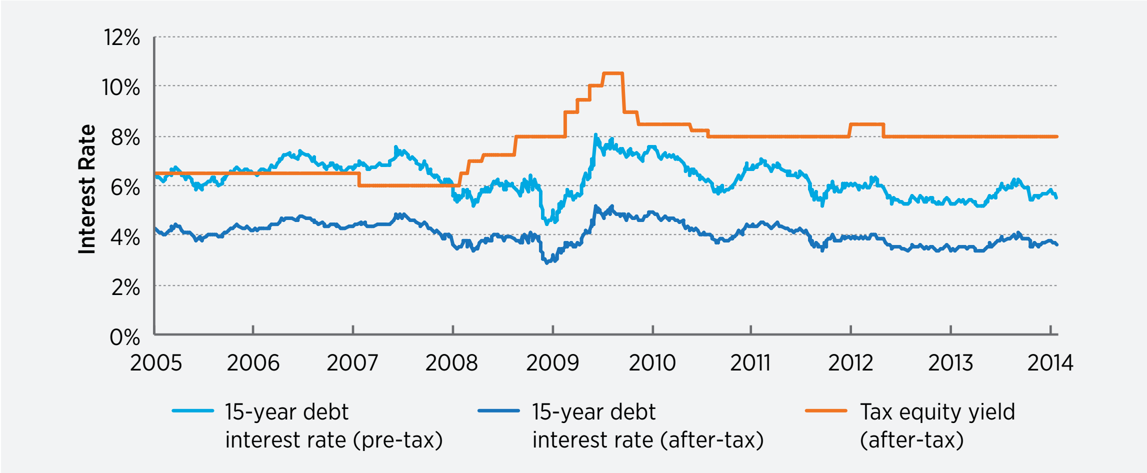
Aside from the lack of clarity in underlying O&M cost trends, however, inspection and monitoring programs have generally improved over time to focus on preventive maintenance for gearboxes, generators, blades, and related equipment. These programs combine information from condition monitoring systems,[14] supervisory control and data acquisition (known as SCADA), asset management software, and increased technical experience to identify trends and proactively ensure wind power plants run at high availability at the lowest possible costs. Turbine manufacturers are also now signing full-service O&M contracts lasting up to 20 years, compared to historical O&M contracts of just two to five years. This indicates increasing confidence in wind technology reliability and the ability to generate revenue by operating wind plants.



Source: Wiser and Bolinger 2014 [6]

Figure 2-9. Installed wind power project costs over time

14. Condition monitoring systems use sensors that measure key operating characteristics of gearboxes, generators, blades, and related equipment to alert operators when non-standard operating conditions occur. Condition monitoring systems are a major component of predictive maintenance.



Source: Wiser and Bolinger 2014 [6]

Figure 2-10. Cost of 15-year debt and tax equity for utility-scale wind projects over time

Project Financing

Wind power is capital intensive, which makes costs for wind highly sensitive to the cost of capital. In the United States, the weighted average cost of capital available to wind project sponsors is artificially inflated by the fact that federal incentives for wind power development are delivered through the tax code (see Section 2.1.2). Most wind project sponsors do not have sufficient "tax liability" to fully benefit from these federal tax incentives, and so they need to rely on third-party tax equity investors to monetize them. This third-party tax equity, however, is a relatively more expensive source of capital. As shown in Figure 2-10, tax equity is currently more than twice as expensive (on an after-tax basis) as the term debt that would likely replace it if monetization were not necessary.[15]

Even the minority of project sponsors that are able to take the tax credits directly on their own (and so do not need to partner with tax equity investors) will often end up with a suboptimal capital structure because they cannot borrow as effectively against PTCs as against cash revenue. Collectively, these impacts of tax incentives on capital structure and cost suggest that altering how federal incentives for wind power deployment are delivered could significantly reduce the cost of capital available to wind project sponsors, allowing wind PPA prices and the LCOE to decline commensurately [32].

Project Performance

Since the early 2000s, turbine manufacturers have developed turbines featuring larger rotors and higher hub heights capable of economically generating power at lower wind speed sites (average wind speeds of less than 7.5 m/s) (see Section 2.5). These substantial advances have had the effect of increasing project performance and opening lower wind speed areas of the country for possible land-based wind development [33, 25, 24, 34]. Since 2012, these larger-rotor turbines have been increasingly deployed in higher wind speed locations (where average wind speeds are more than 7.5 m/s), leading to anticipated wind project capacity factors that sometimes exceed 50%. This is well above what was common through 2014 [35, 24].[16] See Section 2.5 for more details about the effects of technology advancement on annual energy capture and LCOE.

15. The returns of equity investors in renewable energy projects are most often expressed on an after-tax basis, because of the significant value that federal tax benefits provide to such projects (e.g., after-tax returns can be higher than pre-tax returns). In order to accurately compare the cost of debt (which is quoted on a pre-tax basis) to tax equity (described in after-tax terms), one must first convert the pre-tax debt interest rate to its after-tax equivalent (to reflect the tax-deductibility of interest payments) by multiplying it by 65%, or 100% minus an assumed marginal tax rate of 35%.

16. Capacity factor is a measure of the productivity of a power plant, calculated as the amount of energy that the plant produces over a set time period (typically a year) divided by the amount of energy that would have been produced if the plant had been running at full capacity during that same time interval.

As previously mentioned, turbine manufacturers now sign full-service O&M contracts lasting up to 20 years, demonstrating increased confidence in wind technology and revenue potential.

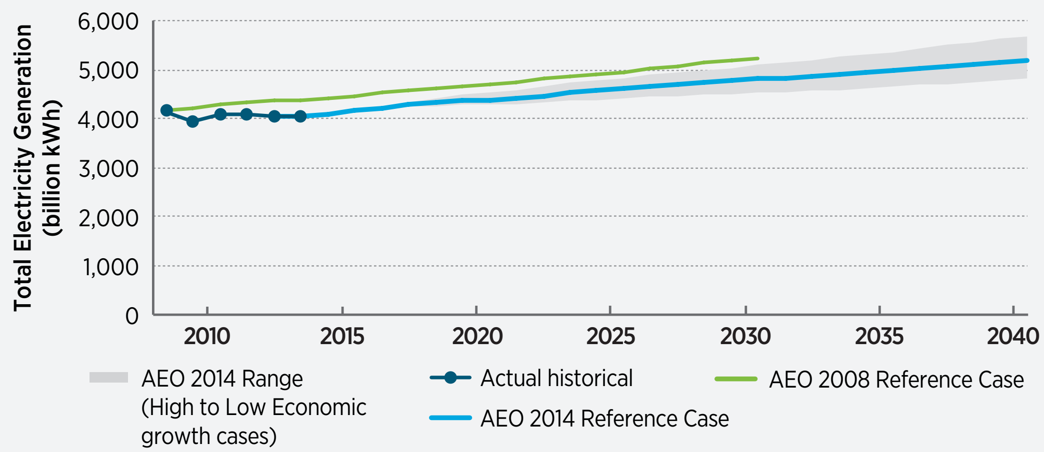
2.1.4 U.S. Electricity Supply and Demand

Wind power deployment is impacted by broader trends in the energy market, including electricity load, the price of other energy sources, and electric power plant retirements. As other forms of electricity generation face regulatory and market challenges, wind power has become a cost effective source of energy, in part due to its declining costs. Despite flat electricity demand and declining natural gas prices, wind deployment has still increased.

Electricity Load

Low electricity load growth since 2008 has reduced the need for new electricity generation. As shown in Figure 2-11, the actual amount of electricity generation required to meet load since 2008 has been largely flat. This generation has also been far lower than what the EIA predicted in its Annual Energy Outlook (AEO) in 2008,[17] though some increase in load was experienced between 2012 and 2013. These lower levels of electricity demand have created a more challenging economic environment for wind; without as much need for new supply, new wind projects need to compete to a greater extent with existing—rather than new—forms of generation.

Electricity supply is projected to grow an average of 0.9% per year through 2040, a minimal change from the 1% per year that was predicted in 2008 [36, 37]. Flat load growth since 2008 means that even the "high economic growth" projection from the AEO 2013 [37] falls below the AEO 2008 reference case projection [36]. While the exact load growth is uncertain, lower levels of projected electricity demand are expected to continue to create a challenging economic environment for wind. If load growth exceeds expectations, however, wind deployment could increase more than anticipated. One study, for example, estimated that transportation electrification could generate nearly 500 billion kWh of new annual demand by 2050, or almost 13% of 2013 U.S. net electric power sector generation [3, 38].

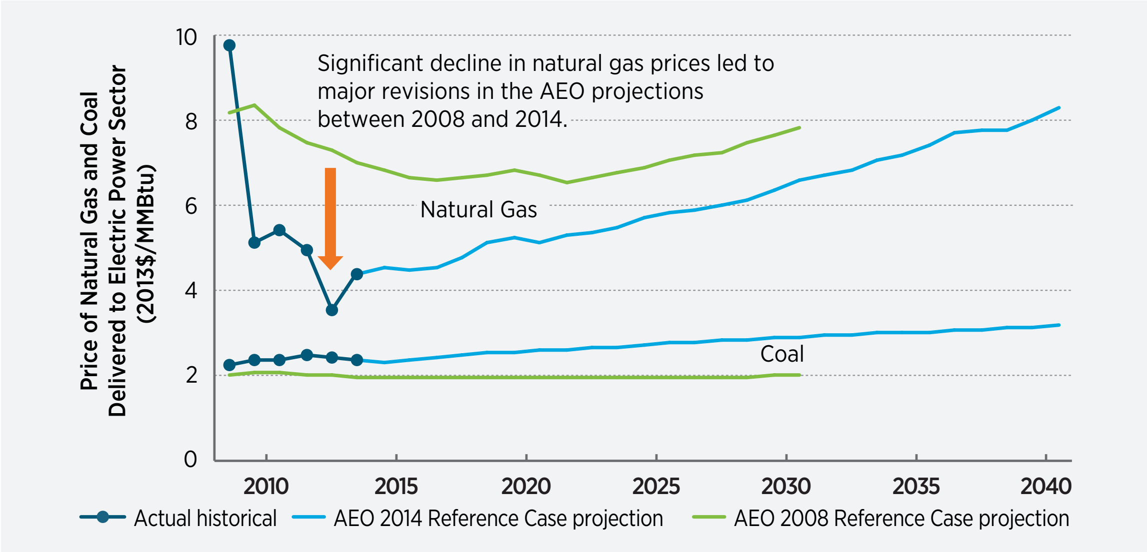


Note: EIA publishes the *Annual Energy Outlook* to project energy and fuel costs. The Reference Case is the main 'central' estimate reported. There are several additional cases that project energy demand and costs under a variety of economic and fuel cost conditions. The range illustrated above depends on a range of economic growth assumptions.

Source: EIA [42]

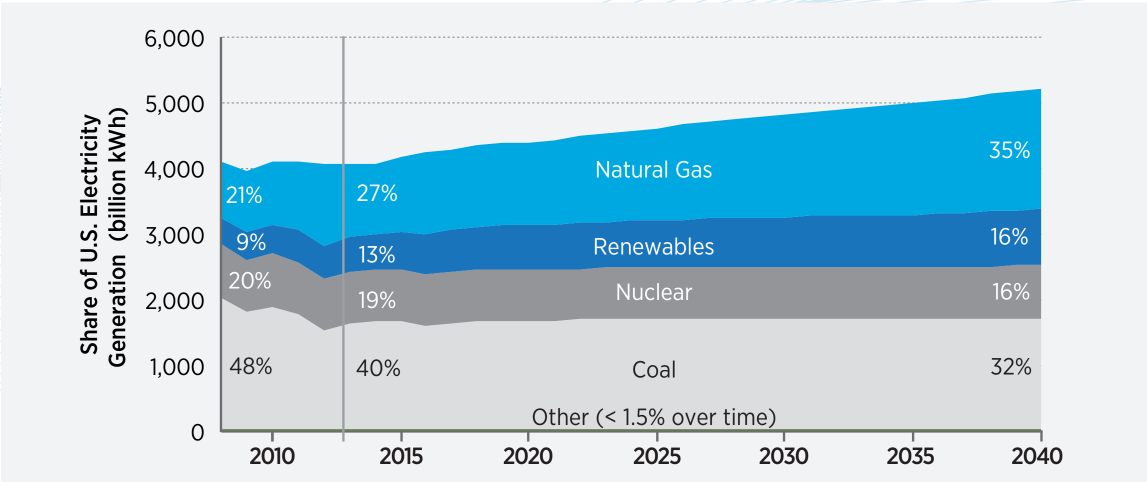
Figure 2-11. AEO projected load growth cases vs. actual

17. The DOE Energy Information Administration produces an Annual Energy Outlook, which defines a "reference case" and specifies "high" and "low" ranges of projected electricity generation for analytical purposes, The AEO is available at: *http://www.eia.gov/forecasts/aeo/*.



Source: EIA [42]

Figure 2-12. Natural gas and coal prices and projections from two AEO Reference Cases



Source: EIA [42]

Figure 2-13. Historical and projected U.S. electricity generation by fuel in AEO Reference Case 2014

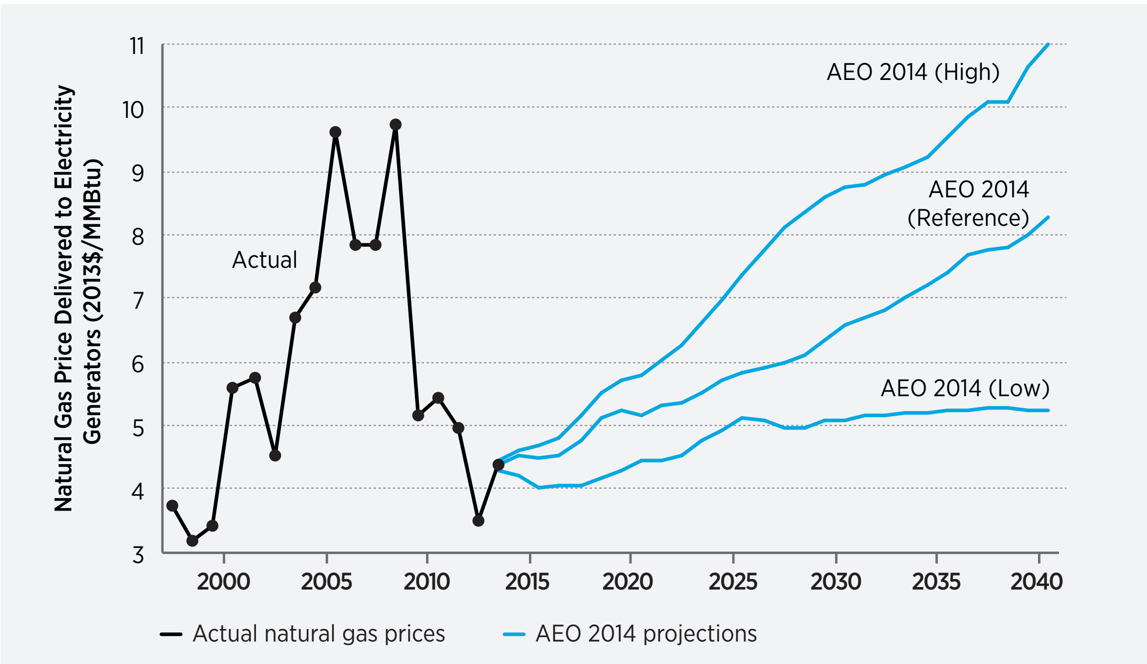
Natural Gas Prices

Since 2008, the increase in natural gas reserves enabled by advances in horizontal drilling and hydraulic fracturing has been among the more important energy supply-side developments impacting wind power [39, 40]. In response to this new supply (along with tepid demand from a sluggish economy), natural gas prices have fallen dramatically from their peak in mid-2008 (Figure 2-12), prompting a considerable amount of fuel-switching in the power sector (Figure 2-13). The share of natural gas-fired generation in the U.S. power mix increased from 21% in 2008 to 27% in 2013 [41], while coal-fired generation declined from 48% to 37% over this same period. Though coal prices have remained relatively steady, these developments with natural gas have pushed wholesale power prices down from the highs seen in 2008 (Figure 2-12), resulting in increased competitive pressures for wind power.

The future generation mix, especially the share of natural gas-fired generators, will affect the market competitiveness of wind power (Figure 2-13). Although natural gas prices (and price projections) remain below 2008 levels, prices have already recovered somewhat from lows seen in 2012. Natural gas prices are projected to increase further through at least 2040, as demand increases due to anticipated economic growth and opportunities to export natural gas or use it for transport (Figure 2-14).

Increased use of natural gas for electricity offers positive effects for wind generation because gas's price elasticity makes wind more competitive. Greater numbers of natural gas power plants, however, have the potential to create competition for wind. Because natural gas power plants can vary their generation output more quickly than coal or nuclear plants, they offer utilities greater flexibility to respond to changes in wind power output.

As of 2013, low natural gas prices and expectations about future price make it more difficult for wind to compete on economic grounds [43]. Still, it is important to recognize that natural gas prices have historically been unpredictable. The 2013 EIA AEO [37] projected a wide range of prices between the low, reference, and high gas price cases, from less than $5.50/million British thermal units, or MMBtu, to greater than $10.50/MMBtu in 2040 (Figure 2-14). This price uncertainty stems from unclear demand, lack of clarity on the future amount of liquefied natural gas exports, public concerns about hydraulic fracturing, and uncertainty about the size of the domestic natural gas resource base [43]. The potential negative impact of gas price uncertainty and volatility on consumer costs is exacerbated by the challenge of effectively hedging gas prices over longer terms [43]. While these factors also lead to uncertainty about the future competitiveness of wind vs. gas—and, therefore, future wind deployment—they also highlight the possible role that wind might play as a hedge against some of these risks. This topic is explored further in Section 2.4.6 and in Chapter 3.



Note: EIA publishes the *Annual Energy Outlook* to project energy and fuel costs. The Reference Case is the main 'central' estimate reported. The High and Low projections of this figure refer to AEO's Low Oil and Gas Resource and High Oil and Gas Resource Cases, respectively.

Source: Lawrence Berkeley National Laboratory compilation of forecasts and data from EIA

Figure 2-14. Actual natural gas prices and AEO forecasts

Table 2-1. EPA Rules under Development in 2014 Affecting Power Plants

Rule	Goal	Initially Planned Effective Year	Status (2014)
Cross States Air Pollution Rule	Limit air pollution transport	2012	Upheld by Supreme Court in April 2014
Mercury and Air Toxins	Limit mercury and other hazardous gases	2015	Upheld by Appeals Court in April 2014
Coal Combustion Residual	Manage safe disposal of coal ash	Pending final rule	Near final, but the rule could take two different routes
Cooling Water Intake Structures § 316(b)	Protect fish and aquatic life	2021	EPA finalized standards in May 2014
Guidelines to Clean Air Act Section 111(d)	Reduce carbon pollution from the power sector	2015	Released draft in June 2014 and a final rule by June 2015

Source: Adapted from information from the U.S. Environmental Protection Agency

Power Plant Retirements

Retirement of conventional power plants will affect the future potential for wind deployment. Retirements of coal and nuclear power plants have already occurred as a result of competition with lower-cost natural gas plants. In locations in which wind power can compete economically with natural gas, that conventional generation can be replaced with wind power. Environmental regulations will also influence decisions about power plant technologies. As of early 2014, new EPA rules about environmental concerns other than GHGs were in varying stages of development and implementation (Table 2-1). Additional policies potentially affecting wind deployment are discussed in Section 2.1.5.

Two GHG-specific rules are also under development by the EPA for new and existing power plants as of 2014. The first rule, which has been released in proposed form, could prevent construction of new coal plants unless they integrate carbon capture and sequestration technology [44]. The second rule, focused on existing plants and released in draft form in 2014, could result in additional retirement of fossil generators.

Proposed changes to the Clean Air Act Section 111(d) were introduced in 2014 as well (Table 2-1). In this action, the EPA proposed state-specific, rate-based goals for CO_2 emissions from the power sector, as well as guidelines for states to follow in developing plans to achieve the state-specific goals. This rule would continue progress already underway to reduce CO_2 emissions from existing fossil fuel-fired power plants in the United States.

Numerous studies have analyzed which power plants would likely be impacted from investment in new technologies to comply with the possible forthcoming rules, and which would be more advantageous to retire [40]. Many of these studies estimate that these rules could lead to an increased cost of fossil fuel-fired generation and the retirement of 45–70 GW of coal plants by 2020. For example, an August 2013 survey indicates that, since 2006, 58 GW of coal plants have announced retirements by 2025 [45]. Coal plant retirements are projected to be greater if proposed GHG rules are also considered.

Nuclear plant retirements are anticipated in part due to lower natural gas prices. The catastrophic failure of Japan's Fukushima I Nuclear Power Plant has also increased scrutiny of nuclear safety. A 2013 study found that up to 38 nuclear reactors are "at risk" of retiring early [46]. Announcements had been made by the end of 2013 to close several nuclear plants, including San Onofre, California; Crystal River, Florida; Kewaunee, Wisconsin; and Vermont Yankee, Vermont.

2.1.5 Market Drivers and Policy

Rising wholesale electricity prices and growth of renewable energy incentives, helped facilitate the expansion of wind power. Policy uncertainty, low natural gas prices, modest electricity demand growth, and limited additional demand from state RPS policies will continue to affect the wind industry. Cycles of wind deployment have been created by short-term extensions and periodic expirations of federal tax incentives. This fluctuating market creates challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders.

Federal and State Policy for Wind

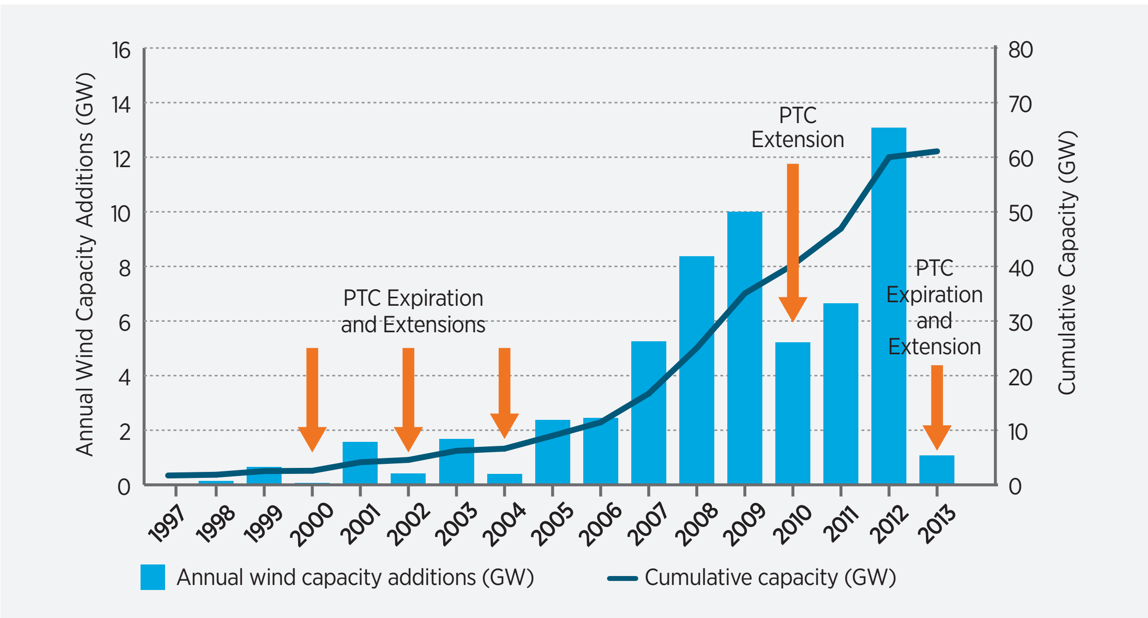
Various federal and state policies have underpinned the domestic wind power market since the industry's beginnings in the 1980s [47]. The most influential federal policy is the PTC as first enacted through the Energy Policy Act of 1992, H.R.776. Later provisions included the investment tax credit (ITC) and a provision under the American Recovery and Reinvestment Act of 2009—known as the Recovery Act—that enabled wind power projects to elect, for a limited time, a 30% cash grant in lieu of the PTC or ITC [25].[18]

As of 2013, 29 states plus Washington, D.C., had mandatory RPS programs. Though direct correlations between RPSs and the amount of wind development are not clear [48, 49, 50, 51], and RPSs are not the only driver of development, 69% of wind power capacity added in the United States from 1999 through 2013 was located in states with RPS policies. Beyond RPSs, state policies that have supported growth of the wind industry include utility resource planning efforts, state renewable energy funds, voluntary "green power" programs, various forms of state tax incentives, and state and regional carbon-reduction policies [25].

Policy Uncertainty and Incremental Growth Trends

Federal and state policies have been integral to the success of the wind industry.

As shown in Figure 2-15, wind deployment has dropped significantly each of the four times the PTC



On January 1, 2014, the PTC expired again and lapsed for more than 11 months. In early December 2014, the PTC was extended again, but was valid only through year-end 2014.

Sources: American Wind Energy Association

Figure 2-15. Historical wind deployment variability and the PTC

18. The Database of State Incentives for Renewable Energy provides additional information on state and federal renewable energy policies at *www.dsireusa.org*, as does the United States Department of Agriculture Rural Development Energy Programs website, *http://www.rd.usda.gov/programs-services/rural-economic-development-loan-grant-program*.

Text Box 2-2.

Key Federal Policies Affecting Wind Power

PTC and ITC: Originally enacted in the Energy Policy Act of 1992, the PTC is a production-based tax credit available to various renewable energy sources. The PTC provided a 2.3¢/kWh tax credit for the first 10 years of electricity generation for utility-scale wind. The ITC (available as of 2013) provides a credit for 30% of investment costs and is especially significant for the offshore and distributed wind sectors because such projects are more capital-intensive than land-based. In January 2013, the PTC and ITC were extended through the American Taxpayer Relief Act. Wind power projects larger than 100 kW can qualify for the PTC or ITC if construction was started before January 1, 2014 (turbines under 100 kW are eligible until 2016), by satisfying the "program of continuous construction" and "continuous efforts," and being placed into service by the end of 2015.

Recovery Act: The American Recovery and Reinvestment Act of 2009 (Pub.L. 111–5), known as ARRA or the Recovery Act, allowed wind projects to take the ITC in lieu of the PTC. ARRA also created the Section 1603 Treasury grant, a temporary program that enabled specified energy property built by the end of 2012—including wind projects—to receive a cash grant of 30% of a project's capital costs in lieu of either the PTC or ITC. Given the challenges in securing tax equity during the financial crisis, Section 1603 has been credited with supporting the continued growth of the renewable energy sector during what otherwise was a challenging investment environment. The program also reduced barriers for newer and less-experienced wind developers, who might otherwise have faced sizable challenges in accessing the limited supply of tax equity. The proportion of wind power additions supported by the grant include 44% of new wind capacity installed in 2012, 62% in 2011, 82% in 2010, and 66% in 2009. ARRA also created the Section 1705 loan guarantee program for commercial projects, which closed on four loan guarantees to wind projects totaling more than 1,000 MW.

Accelerated Depreciation: Accelerated depreciation through the federal Modified Accelerated Cost-Recovery System, known as MACRS, allows wind project owners to depreciate most project capital costs on a five-year schedule. The Economic Stimulus Act of 2008 (Pub.L. 110–185, 122 Stat. 613) and subsequent legislation provided a further 50% first-year bonus depreciation provision for projects built between 2008 and 2010. The American Taxpayer Relief Act of 2012 (Pub.L. 112–240, H.R. 8, 126 Stat. 2313), extended a 50%, first-year bonus depreciation to projects placed in service through December 31, 2013.

has expired, as well as during the economic downturn and during the onset of increased shale gas availability around 2009–2010. Wind has also experienced *increased* development in years in which incentives are otherwise scheduled to expire by year-end, as projects rush to meet tax incentive eligibility rules. The "boom-and-bust" cycle created by short-term extensions and periodic expirations of federal tax incentives has created challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders [52].

At the state level, many RPS policies are close to being fully met. As a result, the incremental demand for renewable energy under these existing programs is somewhat limited. Lawrence Berkeley National Laboratory (LBNL) projects 3–4 GW/year of new renewable energy through 2025 [6]. Bloomberg projects that 2 GW/year may come from wind, whereas the American Wind Energy Association (AWEA) forecasts roughly 2.4 GW/year of wind from 2013–2025 [53]. These figures are well below annual wind power capacity additions as of 2013. The nature, design, and stringency of future policy drivers that might affect wind installations are uncertain.

2.1.6 Conclusions

Global wind power capacity, generation, and investment have grown dramatically since the late 1990s, and wind power is an important contributor to domestic power generation in the United States. The LCOE of wind in good to excellent wind resource sites dropped by more than one-third over the five-year period from 2009 to 2013 [6], and, in some of the strongest wind markets, wind is competitive with traditional fossil generation [6]. Trends in the cost of wind power and the related prices negotiated in PPAs impact wind power deployment. The LCOE of wind, in turn, is influenced by trends in wind project capital costs; ongoing O&M costs; project financing terms; and project performance.

Wind power deployment is impacted by broader trends in the energy market, including electricity demand, the price of other energy sources, and electric power plant retirements. As other forms of electricity generation face regulatory and market challenges, wind power has become a cost effective source of energy, in part due to its declining costs. Despite flat electricity demand and declining natural gas prices, wind deployment has still increased.

The wind industry is also affected by policy uncertainty. Wind deployment cycles have been demonstrably influenced by extensions and periodic expirations of federal tax incentives. This cyclical behavior creates challenges for wind developers, manufacturers, transmission planners, utility purchasers, and other stakeholders. Section 4.9 of the *Wind Vision* roadmap discusses three key areas in which the wind stakeholder community can collaborate with others to maintain the analysis capability necessary to inform policy decision makers, including: comprehensively evaluating the costs, benefits and impacts of energy technologies; refining and applying policy analysis methods; and tracking technology advancement and deployment progress and updating the roadmap.

2.2 Offshore Wind

Global offshore wind deployment offers extensive experience from which the United States can learn—at the close of 2013, a total of 2,080 wind turbines were installed and connected to the electricity grid, in 69 offshore wind plants in 11 countries across Europe. Total installed capacity of these turbines reached nearly 6.6 GW at the end of 2013, producing 24 terawatt-hours (TWh) in a normal wind year, enough to cover 0.7% of the European Union's total electricity consumption. The European Wind Energy Association identified 22 GW of consented[19] offshore wind plants in Europe as of 2013, and plans for offshore wind plants totaling more than 133 GW [2]. Worldwide, more than 200 GW of offshore wind were in the regulatory pipeline at the end of 2012 according to assessments by the National Renewable Energy Laboratory (NREL) [54].

Section 2.2.1 discusses trends in the U.S. offshore industry, while Section 2.2.2 examines current offshore costs. Section 2.2.3 reviews the deployment and siting issues affecting the U.S. offshore industry.

2.2.1 Status of the Offshore Industry

Offshore turbines can be located near load centers with some of the highest electric rates in the United States and provide an alternative to long distance transmission of land-based wind power from the Interior to the coasts. The North Atlantic, South Atlantic, Great Lakes, Gulf of Mexico, and West Coast all contain significant offshore wind resources, and projects have been proposed in each of these areas. Environmental organizations in the United States are helping to educate interested parties and are supporting the development of offshore wind. In 2012, the National Wildlife Federation authored, "The Turning Point for Atlantic Offshore Wind Energy," which

Deployment experience in Europe shows that offshore wind is technologically viable. In the United States, offshore is poised for an industry launch.

19. The European Wind Energy Association classifies projects as online, under construction, or consented.

advocates offshore wind development off the Atlantic Coast. The report was endorsed by 40 other environmental organizations [55].

Universities are also leading research on offshore wind. In June 2013, the University of Maine's DeepCwind Consortium launched VolturnUS off the coast of Castine, Maine. VolturnUS comprises a one-eighth scale semi-submersible floating foundation—the first offshore wind turbine deployed in the United States. A number of full-scale projects are also under development within the domestic offshore market. In 2014, Navigant identified 14 offshore wind projects totaling 4,900 MW that had reached an "advanced stage of development [56]."[20] Developer timelines indicate the first of these projects may come online in 2015.

The federal government, including the DOE and the U.S. Department of the Interior (DOI), has also stepped up efforts to accelerate the development of offshore wind. In February 2011, DOE initiated the Offshore Wind Strategic Initiative and launched more than $250 million in public/private research and development funding grants and cooperative agreements. The capstone of this effort is a plan to deploy three Advanced Technology Demonstration projects by 2017. The three finalists for the deployment are Dominion Power (Virginia), Fishermen's Energy (New Jersey), and Principle Power Inc. (Oregon). The federal regulatory process for offshore wind, led by the Bureau of Ocean Energy Management (BOEM), has also evolved considerably since 2008. Following the issuance of the first commercial lease to Cape Wind in 2010, BOEM held successful auctions for three lease areas: off the coasts of Rhode Island/Massachusetts and Virginia in 2013, and off the coast of Maryland in 2014. State regulatory processes in the Great Lakes have also advanced, with issued leases for offshore wind projects in state waters totaling more than 1.2 GW [57].

Despite this progress and the fact that the U.S. offshore wind industry will be able to draw on more than 20 years[21] of international experience with the technology,[22] offshore wind faces several challenges in the United States. Foremost among these concerns is the high cost of offshore wind technology, combined with uncertain policy support [57].

2.2.2 Offshore Costs

Given that no offshore wind projects exist in the United States as of 2014, the costs of such projects is generally uncertain. Some indication about the likely costs of offshore projects can be derived, however, from global experience. During the period 2004–2012, capital costs for offshore wind projects increased as the industry came to terms with the true costs and risks of developing projects in technically challenging offshore sites. Navigant indicates that the average reported cost of offshore wind projects installed globally in 2012 was $5,385/kW[23] [57]. This cost roughly represents a doubling of costs from those observed in the 2002-2007 time period. This increasing cost trend was a result of numerous factors, including:

- A shift toward developing projects in sites characterized by greater water depths, longer distances to shore, and more intense meteorological and ocean conditions;
- A greater understanding of the risks associated with offshore construction, which has resulted in increased spending on risk mitigation as well as higher contingency budgets; and
- A lack of competition in the supply chain—particularly for offshore wind turbines, with 82% of turbines installed in 2012 sold by a single manufacturer [57, 59].

20. *An advanced stage of development* for an offshore wind project is defined as having achieved at least one of the following three milestones: (1) received approval for an interim limited lease or a commercial lease; (2) conducted baseline or geophysical studies at the proposed site with a meteorological tower erected and collecting data, boreholes drilled, or geological and geophysical data acquisition system in use; and/or (3) signed a PPA with a power off-taker [57].

21. The world's first offshore wind park began operation in 1991 in Vindeby, Denmark [58].

22. At the end of 2013, GWEC estimated an installed capacity of approximately 7 GW. The vast majority of this capacity (over 90%) is located in northwestern Europe, where 10 countries have installed offshore wind projects. The remaining capacity is located in Asia, where Chinese, Japanese and South Korean markets show signs of accelerating activity [13].

23. Financial results reported in the 2013 "Offshore Wind Market and Economic Analysis: Annual Market Assessment" Navigant report are in 2011$.

Notwithstanding this trend, data on the near-term project pipeline[24] suggest capital costs appear to be stabilizing. In projects installed in 2013 for which data are available, the average reported capital cost was $5,187/kW, compared to $5,385/kW for projects completed in 2012[25] [56]. While it appears that the stabilizing trend may continue for projects completed in 2014, a lack of data for projects anticipated to reach completion in 2015 and 2016 makes it difficult to assess whether the trend will continue [56].

In the United States, four offshore wind PPAs have been approved to date.[26] All four were motivated at least in part by state policies to encourage utility demand for offshore wind power. The effective bundled prices of these PPAs range from approximately $180/MWh to $240/MWh in 2012 dollars, with terms extending between 15 and 25 years [60]. These PPAs give some indication of domestic offshore wind power prices. Future project and turbine scale increases combined with new technology may further reduce market prices.

The relatively high LCOE for initial offshore wind projects, combined with generally low natural gas prices, means that offshore projects will need stable and long-term policy support. RPSs that reach 30% in the densely populated Northeast will require consideration of offshore wind due to limited space to develop land-based wind and solar at sufficient scale. To facilitate public utility commission approvals allowing utilities to pass the costs of these early offshore wind projects to ratepayers, state legislatures have amended relevant statutes to enable consideration of a range of environmental and economic benefits from the contracts beyond just LCOE (see Chapter 3). Examples include Massachusetts,[27] Rhode Island,[28] and Maryland [57].[29]

It is unlikely that offshore wind projects in the United States will be self-financed. Offshore developers will instead likely seek commercial project financing based on the strength of the market and finance mechanisms, as well as other project contracts and the credit of the power purchaser and other project counterparties. For example, Cape Wind, which has secured long-term PPAs from National Grid and NSTAR, has engaged the Bank of Tokyo-Mitsubishi UFJ, Natixis, and Rabobank [61] as lead arrangers of its debt financing who have committed more than $400 million. For example, Cape Wind secured long-term PPAs and arranged debt financing in 2014 [61, 62, 63]. Wind turbine vendor Siemens has offered to secure financing for the project as needed [63].

2.2.3 Offshore Deployment and Siting

Offshore wind is still in early development phases, but significant progress is being made to facilitate siting, leasing, and construction of offshore wind power projects in both federal and state waters. The main siting concerns focus primarily on questions of competing use, environmental impacts, and constraints due to the availability of technology to meet some challenging design conditions (e.g., water depth issues). Other issues include the timelines and investment required to develop new port facilities, heavy-lift construction vessels, and supply chains for major components. Additional concerns over coastal viewshed issues, understanding of offshore wind resources, and grid interconnection and integration issues also require further investigation.

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24. Near-term pipeline includes projects that are either under construction or have signed major supply contracts as of mid-2014.
25. Financial results reported in the 2014 "Offshore Wind Market and Economic Analysis: Annual Market Assessment" Navigant report are in 2012$.
26. These include: a PPA between NRG Bluewater and Delmarva (canceled by NRG Bluewater in December 2011) enabled by legislation that increased the value of renewable energy credits (RECs) generated by the project to 350% of normal levels, and PPAs between Deepwater Wind and National Grid, Cape Wind and National Grid, and between Cape Wind and NSTAR, all driven by state government interventions that allow the utility to pass through the above-market prices of the contracts, as well as a rate of return, to its customers.
27. The peak demand price suppression benefits of the Cape Wind PPA was cited by both the Massachusetts Department of Public Utilities and the Massachusetts state supreme court when approving the PPA. Alliance to Protect Nantucket Sound v. Department of Public Utilities, 461 Mass. at 176–177, September 8, 2011.
28. Public Law 2010, Chapter 32, amending Title 39 Section 26.1.
29. Maryland enacted legislation in 2013 establishing Offshore Wind Renewable Energy Certificates as a financial support mechanism for offshore wind projects that are approved by the public utility commission, after review of several factors, including reductions of locational marginal pricing, transmission congestion, capacity prices, and other net economic, environmental and public health benefits to the state." (Maryland Code - Public Utilities Article, 7–704.1(D)).

The rapidly evolving federal regulatory process and new state-based policies (in some areas) are supportive of future offshore wind developments in federally designated offshore wind energy areas (WEAs) (Text Box 2-3).

Figure 2-16 identifies the current location and approximate size of the proposed WEAs and other wind development zones that have been proposed, leased, or are under development in state and federal waters. While there has been activity in both state and federal waters, meeting the penetration levels of the *Wind Vision Study Scenario* for offshore wind would require large-scale development under federal jurisdiction on the Outer Continental Shelf (OCS). BOEM is the lead agency charged with leasing offshore wind sites in federal waters on the OCS. The Bureau of Safety and Environmental Enforcement, BOEM's sister agency, is charged with ensuring safe operation of offshore wind on the OCS but has had only a small role as of 2013 because there are no operational U.S. offshore wind projects. Several other federal agencies, including the National Oceanic and Atmospheric Administration (NOAA) and the Army Corps of Engineers, play significant roles in the permitting process. These agencies provide oversight and concurrence to BOEM under its leasing process and, in some cases, are required to issue their own permits.

In 2007, BOEM prepared a programmatic environmental impact statement covering much of the Atlantic coast to support the future regulatory process for leasing offshore wind turbines in the area. BOEM has also developed a series of guidance documents for developers on providing information (e.g., avian surveys, spatial data, and benthic surveys) to support offshore renewable energy permitting. The guidance documents are available on BOEM's website (*www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/)*. In April 2009, BOEM released the primary regulations that provide the framework for offshore renewable energy projects

Text Box 2-3.

Offshore Wind Energy Areas (WEAs)

- BOEM, which controls rights to submerged federal lands, has initiated the "Smart from the Start" program, which aims to facilitate rapid and responsible development of the offshore wind resource [64].
- BOEM has been working with industry, state policymakers, other regulatory agencies, and stakeholder groups to identify priority WEAs on the Atlantic outer continental shelf.
- BOEM has conducted Environmental Assessments in several WEAs and published "Findings of No Significant Impact," which cleared the way for the commercial leasing process and site assessment activities.
- The first leases for development rights within the Rhode Island/Massachusetts WEA and the Virginia WEA have been competitively auctioned. Together these leases grant development rights to more than 270,000 acres of submerged land, which could support up to 5 GW of offshore wind capacity.
- These lease sales, with a total up-front volume of $5.4 million (and additional payments as and if development proceeds), demonstrate the commercial interest in developing offshore wind projects [65, 66].

on the OCS [67].[30] In 2010, DOI initiated a "Smart from the Start" program for siting and leasing offshore wind projects within designated WEAs on the Atlantic coast [68]. Under this framework, BOEM has initiated a process to designate offshore WEAs in close coordination with federal and state regulators, state interagency task forces, and other stakeholders [64]. The WEAs are developed under a broad marine spatial planning process and vetted to minimize conflicts with wildlife and human uses. This effort is conducted in partnership with adjacent states, federal authorities, and major stakeholders.

As part of the analysis of impacts from proposed offshore wind construction, operation, and decommissioning, BOEM considers existing and likely future uses of the coastal and ocean environment and develops best management practices (BMPs) to address potential navigation effects of offshore wind projects. This includes siting of wind plants to avoid unreasonable interference with major ports and Traffic Separation Schemes designated by the U.S. Coast Guard, as well as placing proper lighting and signage on structures to aid navigation and comply with applicable Coast Guard regulations. One example of work to support this is a study published by BOEM to address fishing industry concerns about potential displacement and disruption by offshore wind plant siting. The goal of the study was to work in close consultation with representatives from the fishing industry and wind power developers to develop agreed-upon best management practices and mitigation measures. These best management practices and mitigation tools can be used to develop offset scenarios to support siting analysis and decision making under the National Environmental Policy Act and other applicable statutes. These best management practices will also be used to foster compatible use areas of the OCS and reduce conflicts within portions of the U.S. Atlantic OCS that might be used simultaneously by the wind power industry and fishermen [69]. Results of the study are discussed in the report, "Development of Mitigation Measures to Address Potential Conflicts between Commercial Wind Energy Lessees/Grantees and Commercial Fishers on the Atlantic Outer Continental Shelf."[31]

A primary concern of NOAA's National Marine Fisheries Service is the potential impact on the endangered North Atlantic right whale from survey and construction noise and potential vessel collisions. Several offshore wind developers and environmental organizations reached an agreement on protective mitigation measures such as restrictions on vessel activities during certain periods of whale migration and the use of trained independent observers on survey and construction vessels in the Mid-Atlantic.[32] This agreement was facilitated under guidance and standards set by BOEM.

BOEM will subdivide the larger WEAs into smaller developable leasing areas and auction them off individually to offshore wind developers [70, 71, 72, 73]. This approach addresses requirements for a fair competitive process and results in exclusive site control for the successful bidders. The first two competitively auctioned commercial leases have been awarded through this process, off the coasts of Massachusetts and Rhode Island, and off the coast of Virginia [74, 75]. An additional lease sale occurred in Maryland in 2014. Other lease sales are expected in Massachusetts and New Jersey during 2015.

Some of the wind development zones shown in Figure 2-16 (non-WEAs) were submitted to BOEM as unsolicited lease applications. In these cases, BOEM is required to determine whether there is competitive interest before issuing an exclusive lease. If a competitive interest exists, BOEM holds a lease auction. If no competitive interest exists, BOEM can proceed with the leasing process under a bilateral negotiation with the applicant.

30. The Minerals Management Service was the precursor agency to BOEM and the Bureau of Safety and Environmental Enforcement and was originally designated as the lead agency to support offshore wind development under the Energy Policy Act of 2005.

31. Report is available at *http://www.boem.gov/Draft-Report-on-Fishing-Best-Management-Practices-and-Mitigation-Measures/*.

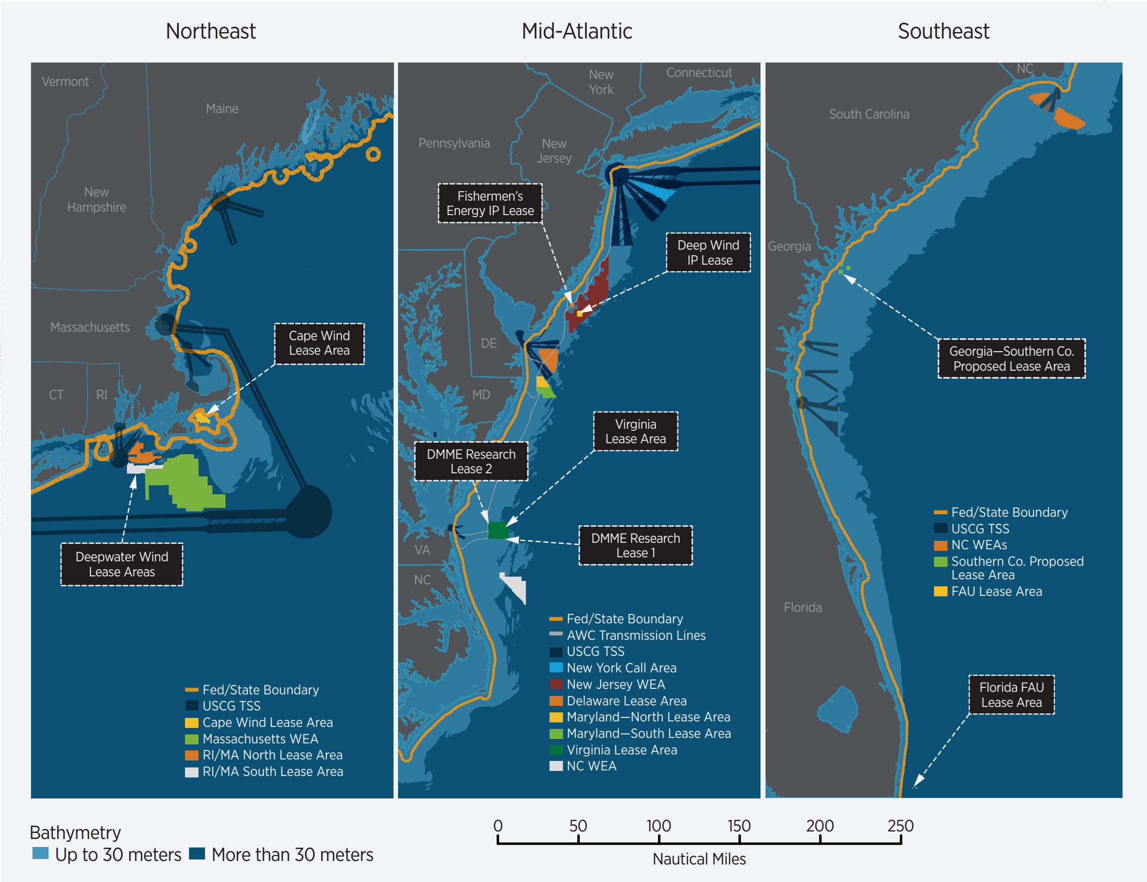
32. "Proposed Mitigation Measures to Protect North Atlantic Right Whales from Site Assessment and Characterization Activities of Offshore Wind power Development in the Mid-Atlantic Wind Energy Areas," letter to BOEM from Deepwater Wind and other developers and Natural Resources Defense Council and other organizations, December 12, 2012.

Examples of unsolicited proposals include:

- Cape Wind, which was granted the first commercial offshore lease in the United States in October 2010 [76][33] before the BOEM review process existed;
- Virginia Offshore Wind Technology Advancement Project- a project conducted by Dominion Power that received a finding of no competitive interest for a research lease to the Virginia Department of Mines, Minerals, and Energy [74]; and
- A 30-MW commercial lease application in Oregon by Principle Power Inc., which received a finding of no competitive interest [69].

Applications also include non-wind projects such as the Atlantic Wind Connection shown in Figure 2-16. This project proposes the installation of a 6 GW offshore grid backbone that could facilitate the distribution of power from North Carolina to New York, but does not include any specific offshore wind power plants.

A few offshore wind projects have been proposed and permitted in state waters (within three nautical miles from the coast in most cases). In addition, many states on the Atlantic coast have proactively established site selection and marine spatial planning processes for state waters that have designated areas for offshore wind development, and have implemented



Note: Bathymetry is the study of underwater depth of lake or ocean floors. Acronyms used in graphic: U.S. Coast Guard (USCG); Coast Guard Traffic Separation Schemes (TSS); Wind Energy Area (WEA); Interim Policy (IP); Virginia Department of Mines, Minerals, and Energy (DMME); Atlantic Wind Connection (AWC); Florida Atlantic University (FAU).

Source: National Renewable Energy Laboratory

Figure 2-16. BOEM-defined wind energy areas for the Eastern seaboard as of November 2013

33. The lease to Cape Wind preceded the current regulations by several years and was granted under a special structure which provided not only site control but was approved as a specific project. This differs significantly from lease practices as of 2013, which only provide site control and initiate the opportunity to study the site and design a project.

project review and permitting processes supporting development. The waters of the Great Lakes are also under state jurisdiction. All offshore wind projects are subject to some level of state permitting due to the need for transmission cables to shore and interconnection with the grid. With so few permitted offshore projects in the United States, however, the regulatory process for offshore wind is largely untested. State agencies lead permitting efforts in state waters, including federal consistency through the Coastal Zone Management Act and state-delegated authority for water quality permits under the Clean Water Act, plus, typically, wetlands approval and a submerged lands lease. Offshore wind plants in state waters also have to comply with all applicable federal regulations.

2.2.4 Conclusions

Deployment experience in Europe confirms that offshore wind is technologically viable. In the United States, offshore projects have been proposed in areas with significant offshore wind resources. Although significant progress is being made to define siting, leasing, and construction procedures for offshore wind power projects, work remains to achieve broader deployment potential for offshore. Some vital steps include continued LCOE reductions and technology advancements, such as floating turbine structures; policy creation and stabilization; decreased regulatory timelines and complexity; development of local supply chains; and enhanced installation logistics capabilities.

The *Wind Vision* roadmap (Chapter 4) discusses actions related to development of a U.S. offshore industry. Section 4.1 discusses the need to collect and analyze data to characterize offshore wind resources and the external design conditions for all coastal regions of the United States. This section of the roadmap also discusses the need to validate forecasting and design tools at heights at which offshore turbines operate. Section 4.2 includes discussion of the need to develop next-generation wind plant technology for rotors, controls, drive trains, towers, and offshore foundations for continued improvements in wind plant performance. The development of an offshore wind manufacturing and supply chain, an important element to offshore wind's contribution to the *Wind Vision Study Scenario*, is discussed in Section 4.3. Section 4.5 reviews the need to develop optimized subsea grid delivery systems and evaluate the integration of offshore wind under multiple arrangements to increase utility confidence in offshore wind, while Section 4.6 discusses the need to develop clear, consistent, and streamlined regulatory guidelines for wind development.

2.3 Distributed Wind

Distributed wind power systems offer reliable electricity generation in a wide variety of settings, including households, schools, farms and ranches, businesses, towns, communities, and remote locations. Distributed wind projects are connected on the customer side of the meter (either physically or virtually[34]) to offset all or a portion of the energy consumption at or near the location of the project, or directly to the local grid to support grid operations. This model differs from the centralized power plant distribution model used by land-based wind plants and offshore wind applications. This section discusses the trends of the U.S. distributed wind industry, including market growth, as well as deployment and siting issues facing the industry.

Distributed wind projects are in all 50 states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. Distributed wind systems often compete with retail electricity rates and have the potential to become more competitive.

Distributed wind systems are used by households, schools, industrial facilities, institutions, municipalities, and other energy consumers. These systems are particularly appropriate in remote or rural locations in which people need or want to produce part or all of their electricity needs. Primarily installed where people

34. Virtually connected distributed wind projects are projects where credits for wind generation not directly connected to the load are applied to customers' bills through remote net metering or meter aggregation. Aggregated, remote, or group net metering authorizes participants to jointly benefit from a single net metered renewable system that is not directly connected to each customer's meter.

live and work, distributed wind projects often serve as "ambassadors" of wind power in that they can often be the public's first exposure to wind turbines.

Because distributed wind is classified based on a wind project's location relative to end-use and power distribution infrastructure, rather than on technology size or project size, the technologies and system sizes can vary significantly. Distributed wind can include small systems of less than 100 kW up to utility-scale turbines of 1 MW and more.

Given the broad applicability of distributed wind project applications, such projects exist in all 50 U.S. states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. This widespread use of distributed wind is significant because some states in the southeastern United States do not have large wind plants, but they all have some type of distributed wind project.

The primary decision-making authorities for distributed wind project permitting are local and state governments. While several states may have permitting processes for large-scale, land-based wind plant projects, few address distributed wind at the state level and only a small portion of cities and counties have permitting processes in place for distributed wind projects. This lack of established standards and familiarity with distributed wind on the part of authorities can create an inefficient and costly project development process for installers and developers who need to navigate through state, local, and utility regulations (or lack thereof), while educating officials along the way. In a step to alleviate this, the Distributed Wind Energy Association (DWEA) published a set of model ordinances and guidelines [77] to lead local governments through adoption of solid and defensible ordinances for turbines used in distributed applications.

The United States is a world leader in the export of small wind turbines (up to 100 kW) used in distributed applications. U.S. small wind turbine manufacturers exported $103 million of small wind turbines in 2013 [78], or nearly a quarter of the value of utility-scale wind exports. Table 2-2 highlights U.S. small wind turbine exports in MWs. The recorded small wind capacity installed worldwide is estimated to be more than 678 MW as of the end of 2012, the last year for which global data are available [79].

Table 2-2. U.S. Small Wind Turbine Manufacturers' Exports and Domestic Sales

Year	Exports (MW)	Domestic Sales (MW)
2006	3	7
2007	4	9
2008	5	13
2009	10	17
2010	8	21
2011	18	15
2012	8	6
2013	14	4

Source: Orrell and Rhoads-Weaver [78]

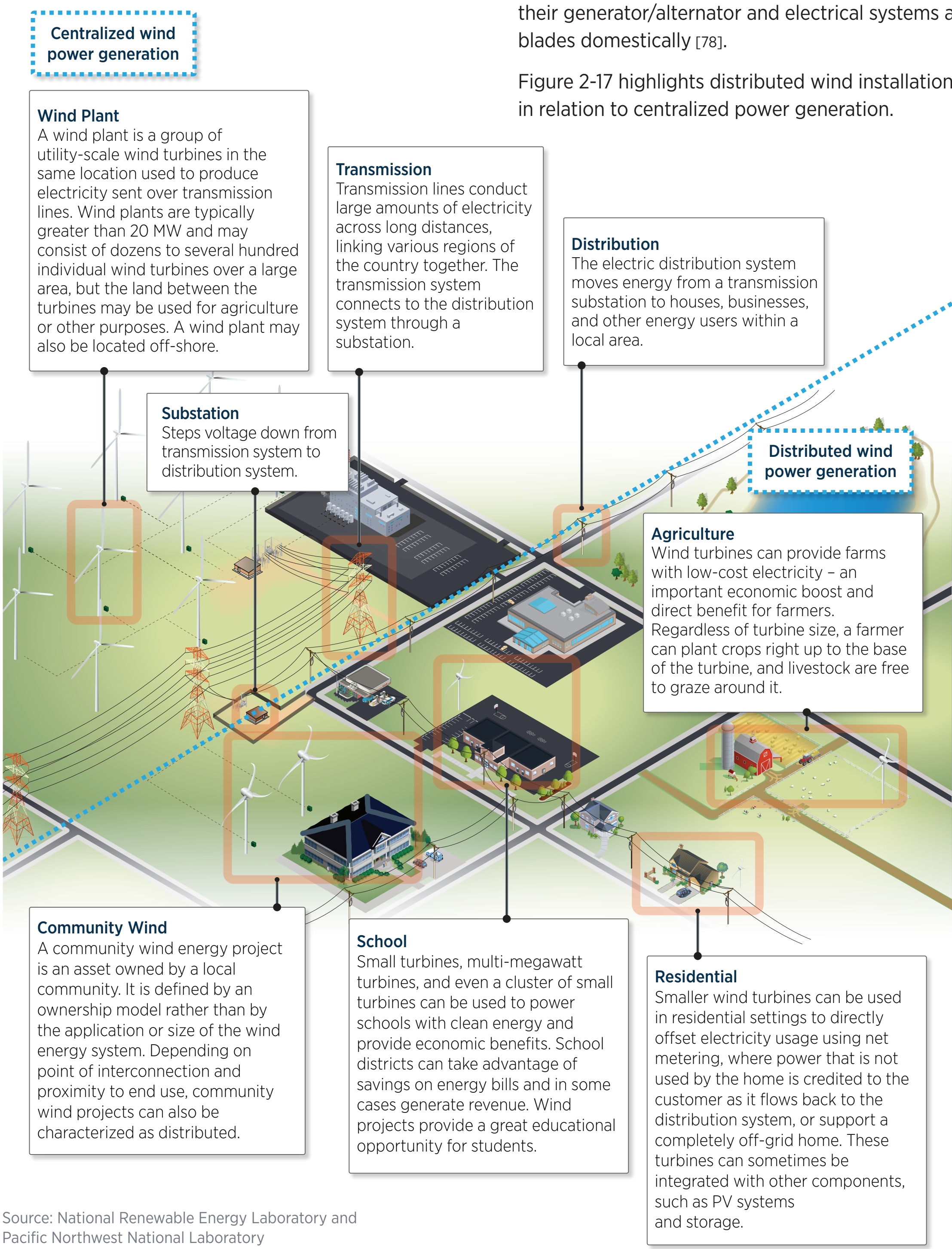
Frameworks and testing facilities have emerged in the United States in recent years to certify small wind turbines to national performance and safety standards, signaling a maturing small wind marketplace. While U.S. manufacturers dominate the small wind turbine market, the distributed wind market depends on imports for turbines larger than 100 kW [80].

Manufacturing facilities for distributed wind systems are widespread. Hundreds of manufacturing facilities and vendors are spread across at least 34 states, comprising:

- at least 31 facilities actively assembling, manufacturing, or refurbishing wind turbines used in distributed applications;
- at least 17 facilities manufacturing wind turbine blades and other composites;
- at least 12 facilities producing wind turbine towers;
- at least 10 facilities producing drive trains and other electrical components;
- dozens manufacturing wind turbine mechanical components; and
- numerous other facilities involved in the manufacturing supply chain (e.g., materials and construction equipment suppliers, financiers, and insurance and other service providers) [78].

Leading U.S.-based small wind turbine manufacturers (i.e., those with large market shares) rely on a largely U.S. supply chain for most of their turbine components, maintaining hardware domestic content levels of 80 to 95% [78]. A total of 13 manufacturers, representing half of 2013 U.S. small wind sales capacity, reported sourcing more than two-thirds of their generator/alternator and electrical systems and blades domestically [78].

Figure 2-17 highlights distributed wind installations in relation to centralized power generation.



Source: National Renewable Energy Laboratory and Pacific Northwest National Laboratory

Figure 2-17. Distributed wind system applications in relation to centralized power generation

Text Box 2-4.

Distributed Wind in Alaska

Alaska, separated from the contiguous United States, is essentially an islanded grid. While dependent on imported resources, such as diesel fuel, Alaska also draws on its own resources to supply its electricity, and wind power is playing a small but increasing role in Alaska's energy generation portfolio. The biggest incentive for wind power development in remote villages of Alaska is the technology's ability to displace the high cost of imported diesel fuel. In the more populated area known as the Railbelt, which includes the city of Anchorage, wind is diversifying the energy mix and providing a hedge against the risk of rising natural gas prices.

While Alaska had 4 MW of installed wind capacity in 2008, it had 59 MW at the end of 2013 [7]. This large increase in installed capacity is mainly the result of multiple projects that went online in 2012, including the 24.6 MW Eva Creek project near Fairbanks and the 17.6 MW Fire Island project in Anchorage (Figure 2-18). The rest of the capacity can be attributed to wind-diesel hybrid systems now operating in more than 20 remote villages. In some cases, these systems provide more than 20% of the village's electrical generation and have made Alaska a world leader in wind-diesel hybrid systems.

Challenges for wind project development in Alaska include the harsh, cold climate; limited human and financial resources; technical challenges associated with integrating wind on small isolated grids; and shipping, construction, and maintenance cost and logistics. Many turbines installed in Alaska have cold weather packages, which may include heating systems for the lubrication system and control cabinets or black blades to reduce ice build-up. In addition, turbines can require special foundation designs to ensure the permafrost ground stays frozen in the summer. Heavy equipment, such as cranes, often can only be mobilized when the permafrost ground is frozen and ice is out of the waterways to allow barge access to deliver equipment and turbine parts. Harsh weather conditions can also delay technicians reaching turbines needing maintenance [81].

Despite these challenges, the citizens of Alaska continue to pursue innovative ways to interconnect more wind power, further reducing the need for high-cost, imported energy resources and increasing the state's energy independence.

Source: Bill Roth/Anchorage Daily News

Figure 2-18. Fire Island 17.6-MW project in Alaska

2.3.1 Conclusions

Distributed wind was a strong growth market from 2008 through 2012, and distributed wind projects are currently in all 50 states, Puerto Rico, the Commonwealth of Northern Marianas, and the U.S. Virgin Islands. Various policy and market conditions—including increased adoption of net metering; increasing retail electricity rates; falling technology costs; and numerous federal, state, and local incentives for distributed generation—could support further growth of distributed wind deployment in the United States. Section 4.5 of the *Wind Vision* roadmap (Wind Electricity Delivery and Integration) discusses the need to improve grid integration of and increase utility confidence in distributed wind systems.

2.4 Economic and Social Impacts of Wind for the Nation

In the United States, wind power is already reducing greenhouse gas emissions as an important part of the electric generation mix. As wind generation displaces generation from carbon-based fuels, harmful emissions and water use by power plants are also reduced. In the process of providing this renewable energy, wind power plants create jobs, a new income source for landowners (lease payments), and tax revenues for local communities in wind development areas. Utilities are using wind to mitigate financial risk within their portfolios with fixed-price contracts of long duration.

Economic benefits of wind power are widespread and include: direct employment, land lease payments, local tax revenue, and lower electricity rates in wind-rich regions. Environmental benefits include substantial reductions in greenhouse gas emissions, air pollutants like oxides of sulfur and nitrogen, and water consumption.

Section 2.4.1 discusses greenhouse gas (GHG) emissions and estimated offsets from wind power. Section 2.4.2 summarizes the economic development impacts of wind power, and workforce development, including job training and workforce safety, is discussed in Section 2.4.3. Air pollution impacts of wind power, water use, and risk and diversity are covered in Sections 2.4.4, 2.4.5, and 2.4.6 respectively.

2.4.1 GHG Emissions

Wind power displaces GHG-emitting generation, which contributes to meeting GHG emission reduction goals. Total energy-related CO_2 emissions in the United States equaled 5.4 billion metric tonnes (5.95 billion short tons) in 2013, of which approximately 35% came from the power sector [82]. Wind power generates no direct emissions, has low life-cycle emissions, and displaces CO_2 and other GHGs that would otherwise be emitted by fossil fuels. Wind power in the United States in 2013 was estimated to have reduced direct power-sector CO_2 emissions by 115 million metric tonnes (127 million short tons), equivalent to eliminating the emissions of 20 million cars during the year [10].

According to the Intergovernmental Panel on Climate Change, the GHG emissions produced in the manufacture, transport, installation, operation, and decommissioning of wind turbines are small compared to the emissions avoided over the lifetime of wind power plants [83, 84]. In addition, the energy consumed for those processes are typically balanced after three to four months of operation at a standard site. Based on an extensive and updated review of studies conducted for the *Wind Vision* impacts analysis (see Chapter 3), the life-cycle GHG emissions of wind are approximately 1% that of subcritical coal, 3% that of combined-cycle natural gas, and comparable to or lower than those of other non-emitting energy sources. Though concerns have been expressed that the variability of wind output (and resultant cycling of fossil plants) might degrade its benefits in reducing GHGs, recent research summarized in Chapter 3 shows that this effect is modest in comparison to wind's emissions reduction benefits[35] [85].

The *20% Wind Energy by 2030* report showed that higher penetrations of wind power could further reduce GHG emissions from the power sector [18], an analysis that is updated and extended in Chapter 3 of the *Wind Vision*. The degree of carbon reduction depends on what power plants are displaced and is regionally dependent [86]. The conclusion that increased wind power reduces GHG emissions, however, has been confirmed by a number of studies conducted by a range of institutions. For example:

- In 2013, the Western Wind and Solar Integration Study showed that achieving 33% wind and solar in the United States portion of the western grid could avoid 29-34% of power-sector CO_2 emissions from the Western grid [87].

35. The incremental fossil plant cycling incurred as a result of meeting 33% of electricity demand in the western United States with wind and solar generation was found to reduce the renewable generation emission reduction benefit by 0.2%.

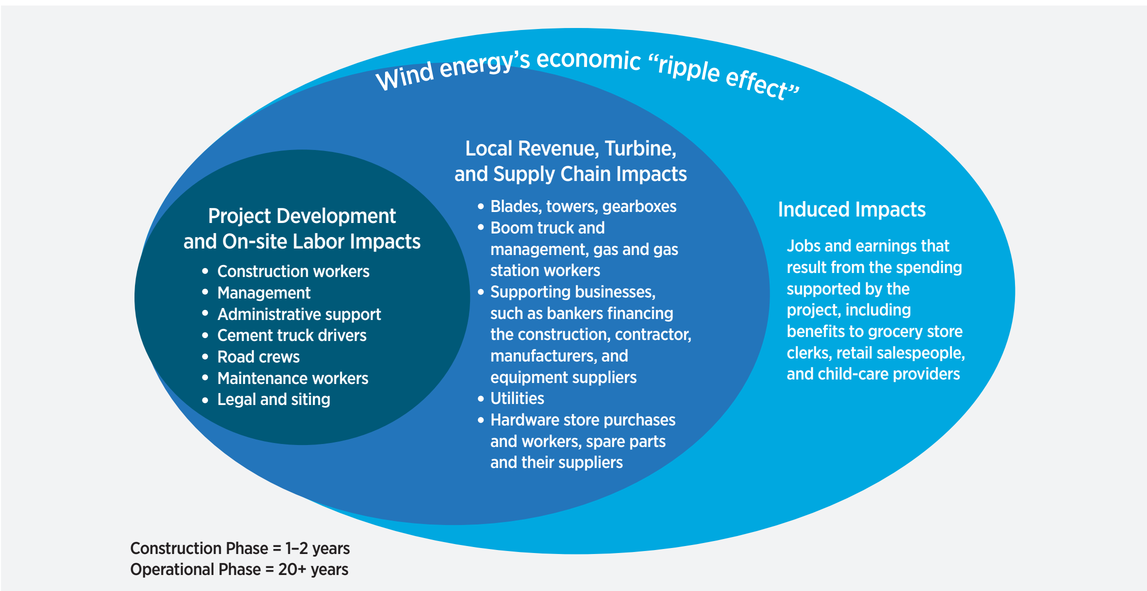
- A 2011 study from Navigant Consulting found that a four-year PTC incentive for wind could spur wind deployment and offset 154.2 million metric tonnes (170 million short tons) of CO_2 from 2011 to 2016 [88].
- Research published in 2014 for the PJM Interconnection power grid operator estimated that 20% wind and solar energy scenarios could reduce the Mid-Atlantic region's power-sector CO_2 emissions by 14-18% vs. a 2% renewables scenario [89].

2.4.2 Economic Development

Wind power development has an economic "ripple effect" for its locality, region, and the nation (Figure 2-19). Wind development and its related manufacturing facilities generate nationwide jobs in sectors such as engineering, construction, transportation, financial, and consultancy services. Future offshore wind installations are expected to open additional opportunities such as repurposing underutilized port infrastructure, employing the maritime trades, and engaging marine science technologies.

Economic development is an important aspect influencing local acceptance of wind power. A 2011 survey conducted in Iowa and west Texas found that more than two-thirds of respondents in several communities near wind plants in the two locations felt their county had benefited economically from wind plants and that the plants were a source of job creation. Support for wind power in these communities was associated with socioeconomic factors rather than foundational aesthetic or moral values; in fact, wind plants were perceived as the vehicle to reverse economic decline [90].

Several national studies have also documented the economic and social impacts of wind development. A 2012 study of 1,009 counties across 12 states with wind development determined that wind power installations between 2000 and 2008 increased county-level personal income by approximately $11,000 and employment of approximately 0.5 jobs for every megawatt (MW) of installed capacity [8]. These estimates translate to a median increase in total county personal income and employment of 0.2% and 0.4% for counties with installed wind power over the same period. A separate study, conducted in 2011, used NREL's Jobs and Economic Development Impacts, model—known as JEDI—to estimate economic impacts from 1,398 MW of wind power development in four rural counties in west Texas. During the four-year construction phase, the study estimated that 4,100 full-time equivalents jobs were supported by this level of capacity. Turbine and supply chain impacts (see Section 2.6) accounted for 58% of all jobs generated. The total economic activity in the local communities was



Source: NREL

Figure 2-19. Economic ripple effects of wind development estimated to be nearly $730 million over the assumed 20-year lifecycle of the plants, or $520,000 (2011$) per MW of installed capacity [91].

A study of the first 1,000 MW of wind power developed in Iowa[36] (between 1999 and 2008) confirmed the following [92] [37]:

- Employment during construction of nearly 2,300 FTE jobs;
- Addition of approximately 270 permanent jobs;
- Total economic activity during construction of nearly $290 million;
- Economic activity during operation of nearly $38 million per year;
- More than $6 million per year generated in property taxes; and
- Nearly $4 million per year provided as lease income to Iowa landowners.

To be clear, these figures focus on gross labor force and economic development impacts related specifically to wind and are not net jobs and economic impacts reported for the state of Iowa.

2.4.3 Workforce

Workforce is a key component of economic development from wind power, and the size of the wind-related workforce has been affected by policy fluctuations that disrupt domestic demand. All 50 states, as well as 71% of the 435 U.S. Congressional districts (held by both parties), had an operating wind project, a wind-related manufacturing facility, or both at the close of 2013 (Figure 2-21) [7]. According to statistics from AWEA, these activities provided jobs in industrial as well as rural areas. Table 2-3 provides a breakdown of wind-related employment in recent years.

New wind projects demand up-front labor for resource assessment, project siting, and permits. In 2012, jobs were lost in the development sector as developers waited for outcomes to uncertainty about the 2013 policy environment and status of the PTC. AWEA reports total jobs linked to the wind industry fell to 50,500 by the close of 2013 [7]. The record installation activity of 2012, however, supported significant increases in construction, transportation, operations, and other project-related jobs, often in rural areas that benefited from the multiplier effects of commercial

Table 2-3. U.S. Employment Linked to Wind Power Development

	2011	2012	2013
Turbine Deployment			
Annual turbine installations	6.8 GW	13.1 GW	1.0 GW
Total turbines operating	38,000	45,000	46,000
Manufacturing			
Manufacturing facilities	470	580	560
Employment			
Total FTE[a] wind jobs	75,000	80,700	50,500
Manufacturing jobs	30,000	25,500	17,400
Construction sector jobs	9,400	16,700	9,600
Wind technician jobs	4,000	7,200	7,300
Other jobs	31,600	31,300	16,200

[a]The American Wind Energy Association tracks and reports U.S. wind power industry employment in terms of full-time equivalents (FTE). This methodology and approach adjusts and accounts for part-time positions such as construction jobs that may only last a few weeks or months during the year or manufacturing positions that only work part-time on wind components.

Sources: AWEA 2014 [7], AWEA 2013 [53]

36. In the Iowa study, equipment and components that were purchased from other states or other countries are treated as monetary leakages and are not included in these estimates.

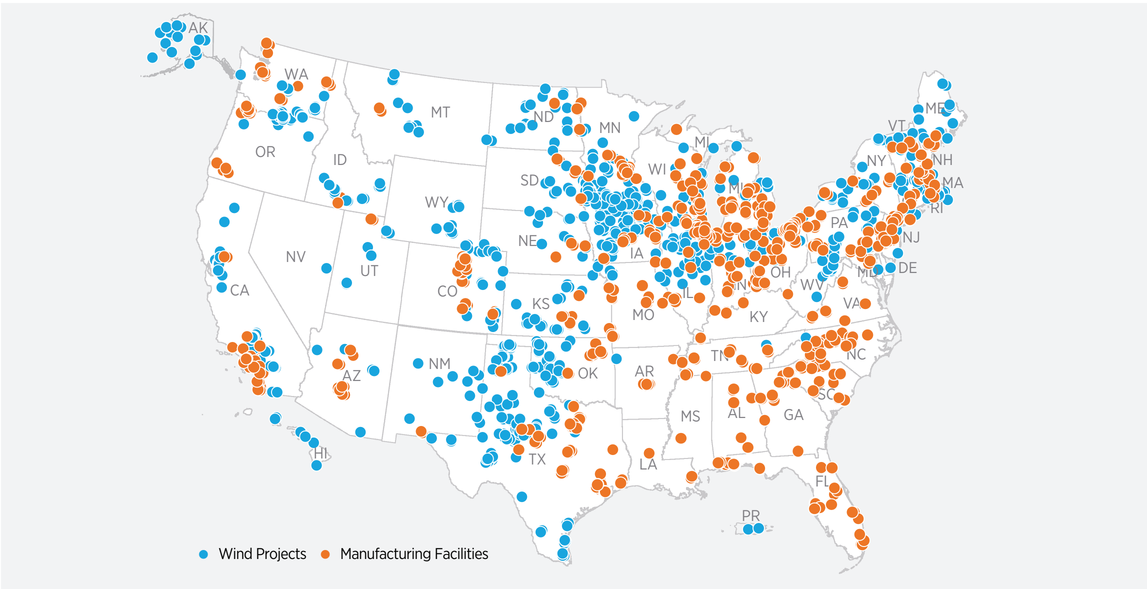
37. Results are in 2010 real (inflation-adjusted) dollars.

activity (Figure 2-20). Although only a little over 1 GW was installed in 11 states in 2013, by the conclusion of 2013 a record 12.3 GW were under construction in more than 90 projects across 20 states [7].

Job Training

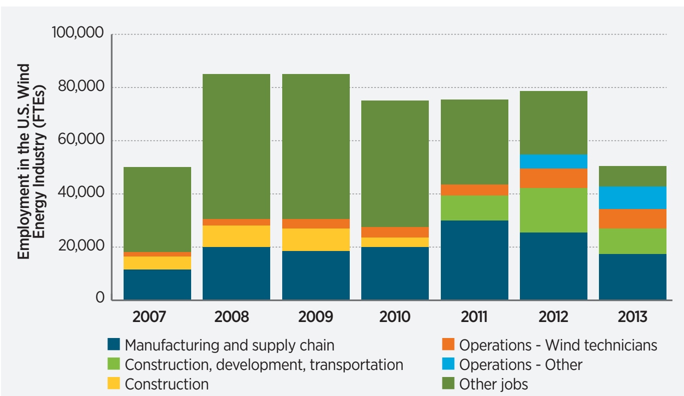
Most of the workers who participated in the rapid expansion of wind power development between 2002 and 2012 came from other market sectors. A 2012 industry survey [93], found that—except for specialized job professions, such as professors, research engineers, and technical specialists—wind-specific educational training was not required, but prior work experience in related fields such as construction or electrical work was considered important to wind industry employers.

By 2013, community and technical colleges were training students to become wind technicians, while an increasing number of universities offered wind power-oriented programs. University-level skill sets and fields needed by the wind power industry include engineering (e.g., electrical, aeronautical, material science, and mechanical), meteorology (e.g.,



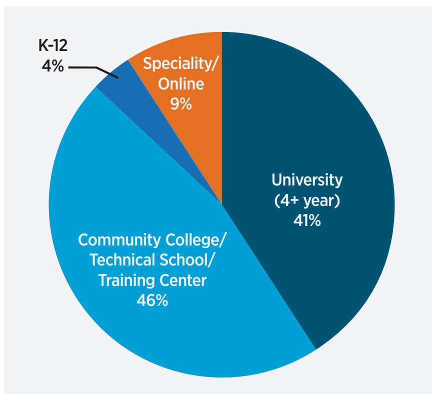
Source: AWEA [7]

Figure 2-20. Active wind-related manufacturing facilities and wind projects in 2013



Source: AWEA [7]

Figure 2-21. Types of jobs supporting wind power development, 2007–2013



Source: AWEA [53]

Figure 2-22. Types of institutions offering wind power programs wind resource assessment, microclimate impacts, and forecasting), biology (e.g., wildlife issues in siting projects), project management, business, law, and government policy (e.g., zoning, planning, and government administration professionals). There is also growing focus on workforce safety as the wind industry has expanded and matured. Text Box 2-5 describes some of the major safety-related activities the wind industry has undertaken.

Wind power education programs have increased at all levels since 2007. Most notably, community college technician training programs grew from six identified in the *2008 20% Wind Energy by 2030* report to more than 100 by 2012 [93]. Three U.S. universities offered a defined Ph.D. program in wind power in 2014 [93]. According to documents from the Executive Office of the President published in 2012, an expected shortfall in engineering graduates could be avoided with a 2012 government initiative to produce one million additional graduates with science, technology, engineering, and math degrees (Report to the Office of the President). The next generation is being exposed to

Text Box 2-5.

Workforce Safety

A number of factors affect safety in the wind industry. For instance, the workforce has varying degrees of experience and training in safety procedures. In addition, short lead times and erratic timing resulting from uncertain government policies and limited equipment availability may lead to rushed installation and commissioning of new wind generation facilities, increasing the potential for accidents and injury. Because most wind plant projects are in remote locations, the availability of adequately trained safety personnel or proximity to first responders may be limited, so continued and increased safety is an important consideration for the wind industry.

Due to the complexity of the worksite and the diversity of related equipment, several levels of procedural training are required for wind plant projects. This training includes personal safety as well as job-specific safety training. Training in safe climbing and self-rescue has become standard in the industry, and other skills such as first aid, CPR, automated external defibrillator use, basic fire safety, proper high voltage electrical safety, and qualified electrical worker training have also been incorporated and implemented. Most companies operating wind sites have developed minimum safety training requirements and are enforcing site rules for visitors and third-party technicians.

The wind industry has raised awareness of worker safety during construction, operation, and maintenance of wind plants. For example:

- AWEA signed an Alliance with the Occupational Safety and Health Administration in 2011 to share information and collaborate to develop compliance assistance materials for the wind industry.
- An AWEA Wind Turbine Risk Assessment subcommittee serves as a forum for owners/operators; original equipment manufacturers; independent service providers, including third party service providers; and other stakeholders to identify potential health and safety issues associated with non-proprietary wind turbine generator design, construction, operation, and maintenance.
- The AWEA Quality Working Group promotes quality assurance during the construction, operation, and scheduled and unscheduled maintenance of wind plants through the generation of tools specifically tailored to wind plant owners and their representatives.
- The AWEA Safety Committee addresses industry issues, such as ladder clearances and the sharing of safety incidents, data, and information among owner-operators.
- AWEA Wind Industry User Groups discuss safety and technical issues and challenges at face-to-face meetings and via pre-established distribution lists, e.g., ListServes.

possible careers in wind power through wind-related curricula at kindergarten through grade 12 schools (e.g., programs from KidWind, WindWise, and the National Energy Education Development Project) and schools that have installed wind turbines (e.g., through initiatives like Wind for Schools).[38] The rapid expansion of wind power in the United States from 2007 to 2009 also spurred efforts to retrain professionals from other industries to enter the wind workforce.

2.4.4 Air Pollution Impacts

No source of electricity is completely benign, and the ways in which wind deployment can impact humans and the environment are addressed later in this chapter as well as in Chapter 3 of the *Wind Vision*. Notwithstanding these local impacts, using wind power to offset fossil generation brings potential public health and environmental benefits, especially in the form of reduced air pollution. Wind power produces no direct air emissions and very low lifecycle emissions (see Chapter 3). Wind generation in 2013 was estimated to have avoided 157,000 metric tonnes (173,000 short tons) of SO_2 emissions and 97,000 metric tonnes (107,000 short tons) of NO_X [10].

Air pollution emissions of particular concern include not only SO_2 and NO_X (and particulate matter, or PM, formed in the atmosphere from those primary emissions), but also directly emitted particulate matter, mercury, and other toxins. In combination, these emissions have wide-ranging negative impacts on human health, economic activity, and ecosystems. In a 2011 rulemaking, the U.S. EPA wrote [94], "…2005 levels of $PM_{2.5}$[39] and ozone were responsible for between 130,000 and 320,000 $PM_{2.5}$-related and 4,700 ozone-related premature deaths, or about 6.1% of total deaths (based on the lower end of the avoided mortality range) from all causes in the continental United States. This same analysis attributed almost 200,000 non-fatal heart attacks, 90,000 hospital admissions due to respiratory or cardiovascular illness, and 2.5 million cases of aggravated asthma among children—among many other impacts." The National Research Council [95], estimated that in 2005, SO_2, NO_X, and particulate emissions from 406 U.S. coal-fired power plants caused aggregate economic damages of $62 billion, mostly from premature deaths associated with particulate matter created by SO_2 emissions. The same study found pollution damages from gas-fueled plants substantially lower, at $740 million.

Chapter 3 provides quantified valuation of the *Wind Vision Study Scenario* in reducing air pollution emissions. This valuation is complicated in part by the nature and stringency of future emissions regulations. Nonetheless, research suggests that these benefits may be substantial. For example, the Siler-Evans et al. [86] estimate the potential benefits of wind power in reducing the health and environmental damages of SO_2, NO_X, and $PM_{2.5}$ emissions from existing power plants. Wind generation is found to reduce air pollution damages valued from near 0.3¢/kWh (in California) to as much as 8.3¢/kWh (in Indiana), demonstrating the sizable range of potential benefits depending on the specific fossil plants displaced by wind power. As with GHG emissions, contemporary research has found that the variability of wind generation and the resultant cycling of fossil plants need not substantially offset wind's emissions reduction benefits (see Chapter 3).

2.4.5 Water Use

In arid parts of the country, water availability has already affected power plant development and operations for technologies other than wind, thus influencing the cost of electricity. Water use includes *withdrawal*, which is water diverted or withdrawn from surface water or groundwater but eventually returned to the source, and *consumption*, which is water that is withdrawn, consumed, and not returned to the source [96]. The power sector is the largest withdrawer of freshwater in the nation; power-sector water consumption is more modest, but can be regionally important. Electricity generation from wind does not use water in appreciable amounts and does not pose a direct systematic impact on water quality. This stands in contrast to thermal power plants (e.g., natural gas, coal, and nuclear energy), which require water for cooling [97]. Wind generation in the United States in 2013 is estimated to have reduced power-sector water consumption by 36.5 billion gallons, equivalent to 116 gallons per person in the U.S. [7].

38. See the following for more information: Wind for Schools (*http://apps2.eere.energy.gov/wind/windexchange/schools_wfs_project.asp*), KidWind (*http://www.kidwind.org/*) and the National Energy education Development Project (*http://www.need.org/*)

39. $PM_{2.5}$ refers to fine particulate matter, i.e., articles less than 2.5 micrometers in diameter. Particles of this size are believed to pose the greatest health risks of all particulate matter.

Text Box 2-6.

Resource Diversity as a Motivation for Buying Wind Power

Public Service Company of Colorado, in reference to its contract with the 200-MW Limon II wind project: "Whenever wind power is generated from the Limon II facility, it will displace fossil-fueled energy on the Public Service system, mostly energy generated from natural gas. We think of this wind contract as an alternative fuel, with known contract pricing over 25 years that will displace fuels where the pricing is not yet known. That is the essence of the fuel hedge" [102].

Google, in reference to several long-term wind contracts into which it has entered: "We see value in getting a long-term embedded hedge. We want to lock in the current electricity price for 20 years. We are making capital investment decisions [regarding data centers] on the order of 15 to 20 years. We would like to lock in our costs over the same period. Electricity is our number one operating expense after head count" [103].

Georgia Power, in reference to its first two wind contracts: "Adding additional wind power to our generation mix underscores our commitment to a diverse portfolio that offers clean, safe, reliable, sustainable and low-cost electricity for years to come" [9].

Xcel Energy, in reference to 850 MW of wind contracts: "It works out to a very good levelized cost for our customers...These prices are so compelling, the energy [cost] associated with it is less than you can do locking in a 20-year gas strip" [9].

Public Service Company of Oklahoma, in reference to procuring triple the amount of wind power than originally planned: "The decision to contract for an additional 400 MW was based on extraordinary pricing opportunities that will lower costs for PSO's customers by an estimated $53 million in the first year of the contracts. Annual savings are expected to grow each year over the lives of the contracts" [9].

Studies evaluating the direct and life-cycle impacts of different forms of electricity generation have confirmed that wind has the lowest level of water use of any electricity generation technology (see Chapter 3 for more detail). One recent study examined total water usage of major energy generation technologies during plant construction, fuel production, and operations. This study determined that, throughout its life cycle, wind power has water use requirements that are orders of magnitude lower than the most water-efficient fossil fuel options [98].

The *20% Wind Energy by 2030* report showed that higher penetrations of wind power could further reduce water use from the power sector [18], an analysis that is updated and extended in the *Wind Vision* (Chapter 3). Power plant development and operations have already been impacted by water availability, especially in areas of the country in which water is scarce, such as the arid West and Southwest. This, in turn, influences the cost of electricity production. These impacts may be exacerbated in the future as a result of global climate change [99, 100]. In reducing water use, wind power can provide both economic and environmental benefits as discussed in Chapter 3.

2.4.6 Risk and Diversity

Risk and uncertainty are defining characteristics of energy supply: for example, fossil fuel prices are uncertain, federal and state regulations change, and electricity load cannot be known with certainty. **Based on several risk categories—construction cost risk, fuel and operating cost risk, new regulation risk, carbon price risk, water constraint risk, capital shock risk, and planning risk—Binz et al. [101] identified land-based wind as not only one of the lowest cost sources of new generation, but also as one of the lowest risk resources overall**. By supplying 4.5% of the U.S. electric power sector end-use demand in 2013, and more than 12% of supply in nine states, wind power is already contributing to a more diverse supply portfolio, thus reducing electric sector risk [7].

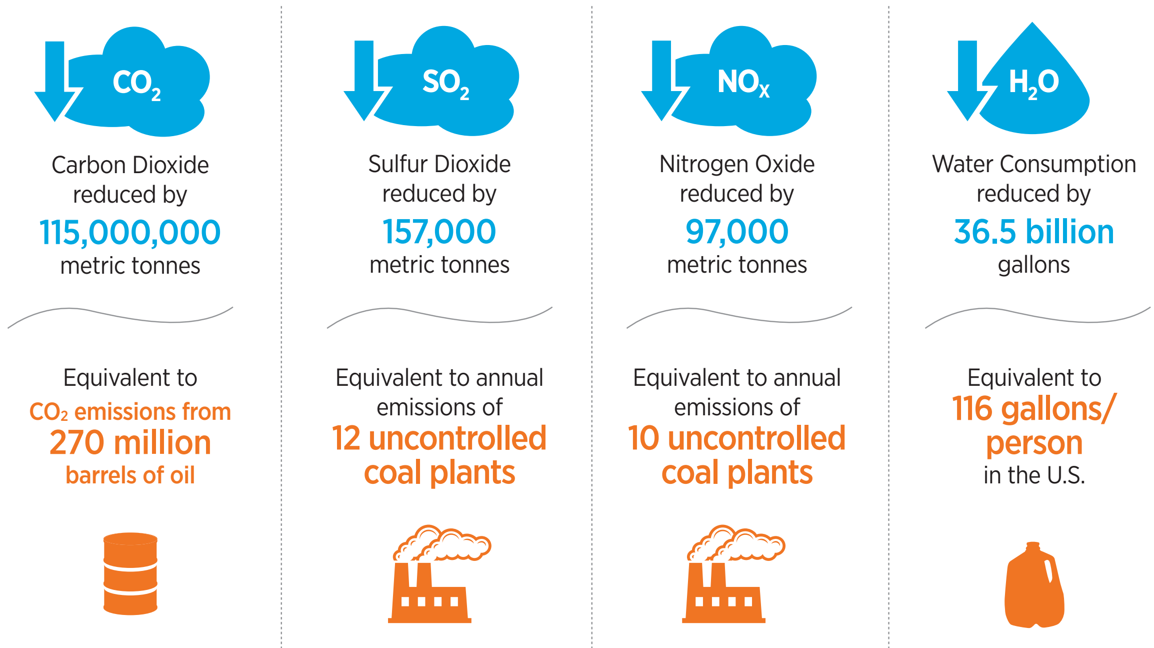
Quantifying the economic value of electricity supply diversity can be a challenge (see Chapter 3 for detailed discussion of this issue). Still, analysis demonstrates that wind can reduce the sensitivity of total energy costs to uncertain long-term changes in fossil fuel prices. As demonstrated by the quotes in Text Box 2-6, a variety of electric utilities and large energy consumers have noted the benefits of energy diversity as a driver for purchases of wind power.

By reducing demand for exhaustible fossil fuels, wind can also place downward pressure on fossil fuel prices, with benefits to energy consumers both within and outside of the electricity sector (i.e., consumers and electric utilities) [52]. This effect, as quantified for the *Wind Vision Study Scenario*, is addressed in detail in Chapter 3. At least in the short run, increased wind power can lower hourly wholesale electricity prices, benefitting electric utilities and consumers who purchase from those markets (albeit at the expense of producers). In a review of many studies, Würzburg et al [104] find a roughly 0.1¢/kWh reduction (within a range of 0.003-0.55¢/kWh) in wholesale prices per percentage penetration of wind power (see Chapter 3).

2.4.7 Conclusions

Wind power provides both economic and environmental benefits to the nation. Economic benefits of wind power are widespread and include direct employment, land lease payments, local tax revenue, and lower electric rates in wind-rich regions. Wind power plant provide jobs, a new income source for landowners (lease payments), and tax revenues for local communities in wind development areas. Utilities are using wind to mitigate financial risk within their portfolios with fixed-price contracts of long duration. Environmental benefits include substantial reductions in GHG emissions, air pollutants like SO_2 and NO_X, and water usage. In the United States, wind power is already reducing GHG emissions as part of the electric generation mix. As wind generation displaces generation from carbon-based fuels, harmful emissions and water use by power plants are also reduced. Figure 2-23 summarizes these emission and water savings.

The deployment levels in the *Wind Vision Study Scenario* require a highly skilled, national workforce guided by specific training standards and defined job credentials. This would enable a sustainable



Note: Emissions and water savings calculated using the EPA's Avoided Emissions and Generation Tool (AVERT). 'Uncontrolled coal plants' are those with no emissions control technology.

Source: AWEA [10]

Figure 2-23. Estimated emissions and water savings resulting from wind generation in 2013 workforce to support the domestic—and, as appropriate—the expanding international wind industry. Section 4.8, Workforce, discusses the *Wind Vision* roadmap actions, including the development of a comprehensive training, workforce, and educational program designed to encourage and anticipate the technical and advanced-degree workforce needed by the industry. Specific actions required include the development of a sustainable university consortium to support research and development efforts; technical training and student collaboration; implementation of an international academic network; creating sustainable wind-focused university programs; and expanding opportunities for student, industry, and university collaboration, such as internships, research fellowships, and joint research projects.

Objective and comprehensive evaluation of different policy mechanisms is needed to achieve wind power deployment that supports national energy, societal and environmental goals while minimizing the cost of meeting those goals in all three wind power markets: land-based, offshore, and distributed. Section 4.9, Policy Analysis, discusses three key areas in which the wind stakeholder community can collaborate to maintain the analysis capability necessary to inform policy decision makers. These collaborative efforts include comprehensively evaluating the costs, benefits and impacts of energy technologies; refining and applying policy analysis methods; tracking technology advancement and deployment progress; and updating the roadmap.

2.5 Wind Technology and Performance

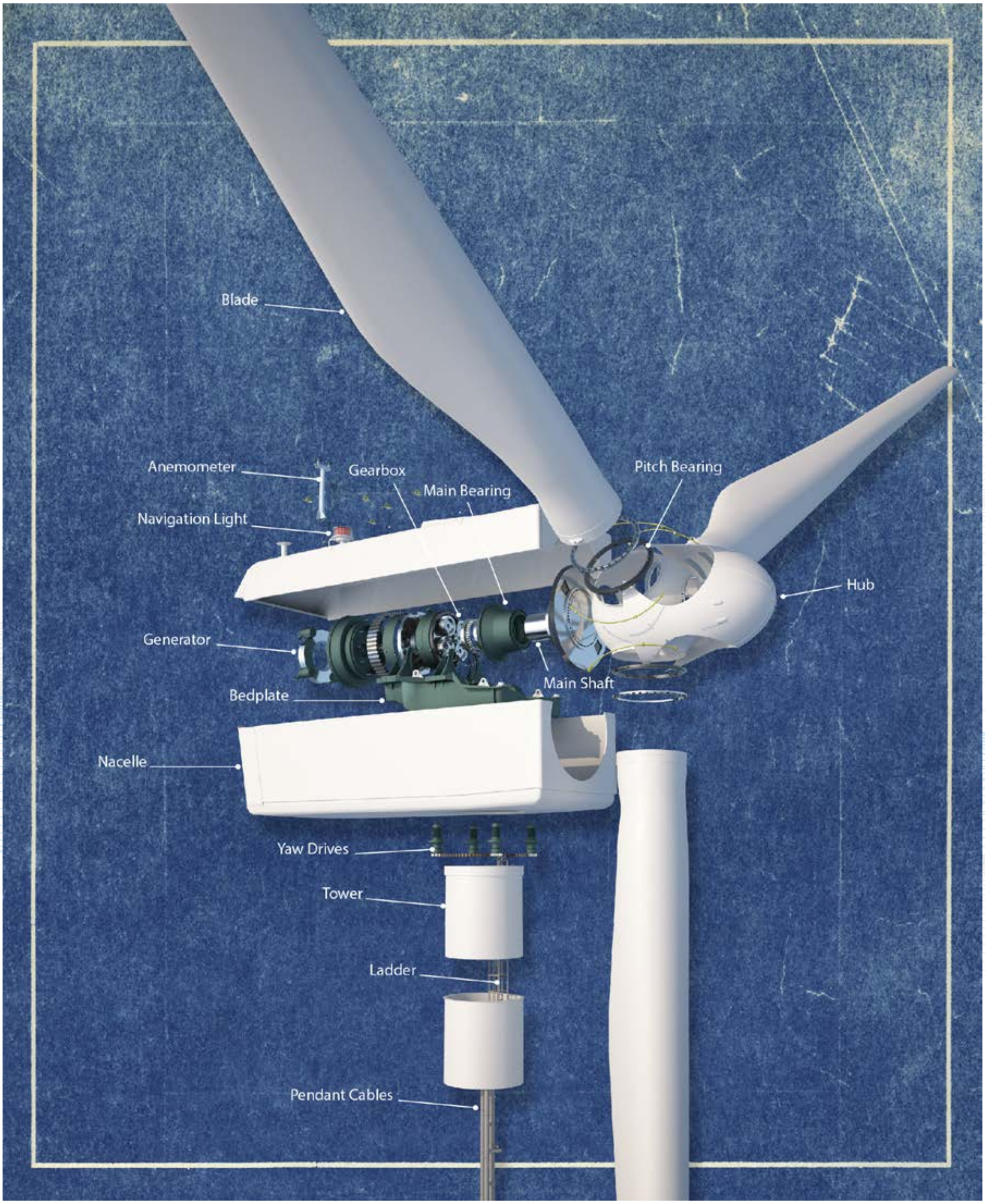
Several decades of technology development and deployed market experience have shown U.S. wind power to be a mature, reliable, and safe technology. Refined estimates raise the U.S. wind resource technical potential on land more than 40% over previous estimates and have increased the confidence level for offshore wind resource estimates [1]. Offshore wind technology has evolved out of land-based systems in Europe and is a major influence on worldwide technology trends. These trends include a push toward large turbines and unique support structures to handle hydrodynamic loading in the offshore environment. Better understanding of the wind resource and continued technology developments are likely to drive on-going trends in improved performance, increased reliability, and reduced cost of wind electricity.

Wind power systems include wind turbine components, individual wind turbines, wind plants comprising arrays of wind turbines, and the interaction of the wind power plant with the electric transmission and distribution grid systems.[40] Significant progress has been made in improving performance and reliability, and in reducing the cost of individual wind turbines. Industry efforts are now shifting to improving overall wind plant performance characteristics.

Technology development and improvements in reliability have helped drive a 33% cost reduction in land-based utility-scale LCOE from 2008–2013

Figure 2-24 illustrates the key components of a typical MW-scale wind turbine. The shape of the *rotor blades* is designed to efficiently convert the power in the wind into mechanical (rotational) power. The wind power that at any given wind speed can be captured by the *rotor* is proportional to its swept area, and larger rotors therefore capture more energy. One of the most complex systems in a wind turbine is the *drive train,* which converts the rotational power from the rotor into electrical power. A key component in the drive train is the *generator*. Most turbines utilize a *gearbox* to increase the rotational speed from the 5–15 revolutions per minute (RPM) of the rotor to the 500–1,800 RPM needed for typical generators. Some turbines omit the gearbox and instead use direct-drive generators that are designed to operate at very low rotor RPMs. Drive train components are housed in a *nacelle*, with the *rotor-nacelle assembly* installed at the top of a *tower*. The tower provides clearance between the rotor and the ground. It is important to note that wind speed generally increases with increased height above the ground, and taller towers therefore provide access to stronger winds.

40. Section 2.5 focuses primarily on utility-scale (1MW+) turbine technology. Small (<100 kW) and mid-sized (100 kw – 1 MW) turbine technologies share some similarities with utility-scale, but a more specific discussion on smaller turbine systems can be found in Section 2.3.



Source: National Renewable Energy Laboratory

Figure 2-24. Illustration of components in a typical MW-scale wind turbine

A wind power plant, or wind plant, is a set of wind turbines that are connected to the electrical transmission grid at a single point. In addition to the wind turbines, the wind plant contains many other components, including foundations for the towers, underground cables to collect the power from the individual turbines, step-up transformers, switchgear, roads, substation, and supervisory control and data acquisition (known as SCADA).

U.S. wind power resource potential, characterization, and future trends are summarized in 2.5.1. Wind plant technology status, including wind turbine scale-up, low wind speed technology, tower technology, blade technology, drive train technology, and control technology are discussed in Section 2.5.2. Section 2.5.3 discusses the current status and trends of wind plant performance and reliability, including capacity factor and the reliability of wind turbine systems, gearboxes, generators, and blades. Aftermarket upgrades, repowering and decommissioning are discussed in Section 2.5.4. Finally, offshore technologies are summarized in Section 2.5.5.

2.5.1 U.S. Wind Power Resource and Resource Characterization

The wind resource technical potential of the United States has been estimated to be 13 times current U.S. electricity end use. While these estimates of technical potential do not consider availability of transmission infrastructure, costs, reliability or time-of-dispatch, current or future electricity loads, or relevant policies, understanding this resource is crucial to tapping wind power.

Resource Potential

The United States has significant wind resources, both on land and offshore. At the time of the *20% Wind Energy by 2030* report [18], it was estimated that the U.S. wind resource technical potential was roughly 7,800 GW for land-based wind and roughly 4,400 GW for offshore shallow and deep water wind combined. These estimates were for turbines at a 50 m (164 ft.) wind tower hub height [105]. In general, the wind resource is better at higher levels above the ground. Refined estimates since 2008 take into account measurements at higher hub heights as well as technology improvements and place the U.S. land-based wind resource technical potential at 90 m hub heights (295 ft.) at roughly 11,000 GW, more than a 40% increase over previous estimates [1]. Offshore wind resource estimates are roughly 4,200 GW [1]. Though offshore estimates have not changed in magnitude with refined analysis, confidence levels for these estimates have improved. As noted, these are all estimates of technical potential and do not consider availability of transmission infrastructure, costs, reliability or time-of-dispatch, current or future electricity loads, or relevant policies. Technical potential estimates are based in part on technology system performance, so potential may change as technologies evolve.

Table 2-4. U.S. Wind Power Technical Resource Potential

	GW	TWh/ Year	Quad/ Year[a]
Land-based wind	11,000	32,700	112
Offshore wind	4,200	17,000	58
Total United States	15,200	49,700	170

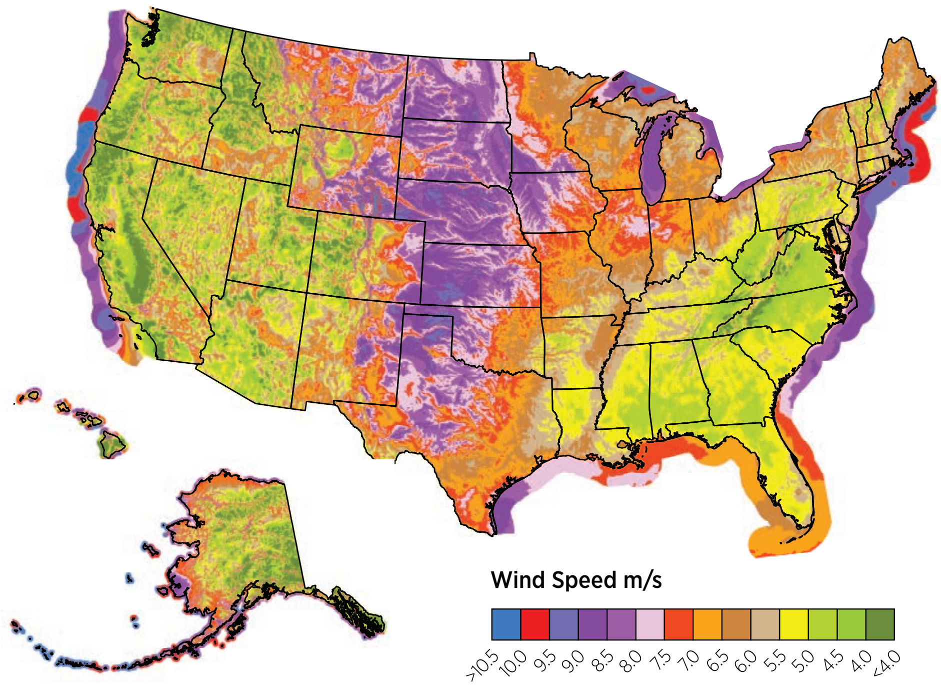
Note: Technical resource potential refers to technology-specific estimates of energy generation potential based on renewable resource availability and quality, technical system performance, topographic limitations, environmental, and land-use constraints only. The estimates do not consider (in most cases) economic or market constraints, and therefore do not represent a level of renewable generation that might actually be deployed.

a. 1 kWh = 3,412 Btu Source: Lopez [1]

The 20-year average of total U.S. primary energy use in all sectors combined is 96.2 quadrillion British Thermal Units (quads) per year, and was 95.0 quads in 2012, the most recent year for which data are available [3]. Of this, end-use electricity consumption was roughly 13 quads. The U.S. wind technical potential of over 15,000 GW is estimated to be able to produce 49,700 terawatt-hours/year, equivalent to 170 quads per year (Table 2-4), or 13 times U.S. electricity end use as of 2013.

These resources on land and offshore, combined with improved turbine and offshore wind technologies, provide the United States with vast wind power opportunities in every geographic region. Figure 2-25 illustrates the U.S. wind resource in terms of wind speed at a 100 m (328 ft.) hub height. More than 1,000 wind turbines have been installed on towers with hub heights of 100 m or more [7].

Improved computational capabilities and advances in wind speed measurement technology, especially remote sensing, have made high-resolution maps and fine spatial resolution databases available to the wind



Source: Wind resource estimates developed by AWS Truepower, LLC. Web: *http://www.awstruepower.com*. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84

Figure 2-25. Annual average U.S. land-based and offshore wind speed at 100 m above the surface

power community. Decreasing computational and data storage costs have allowed the use of more complex wind speed models to map the wind resource at higher spatial resolution on land and offshore, extending numerical domains to cover the entire continental United States with 2.5-kilometer (km) (1.55-mile) resolution. State maps have also been improved with finer levels of detail and at various heights above ground. These numerical resource assessments provide wind developers, utilities, and end users with useful supplements to data from meteorological towers and are an important tool for the detailed siting of wind turbines of all sizes.

Resource Characterization

Wind characterization is important for wind power development and wind plant design. Characterization of the wind, at a minimum, includes quantification of average wind speed and the variability around that average; quantification of seasonal and diurnal variations in the wind speed; wind direction and its correlation with wind speed; turbulence; and vertical shear. Making best use of available wind resources requires technology and operations optimization at both the wind plant and wind-grid system levels. Integral to system optimization is a complete understanding of atmospheric physics—the conditions and dynamics—and how these interact with wind turbine arrays in terms of structural loads and power production. The spatially and temporally dynamic interactions are known as "complex flow" [106]. Models for atmosphere, technology design, and wind forecasting as of 2013 do not accurately portray the atmospheric stability or complex terrain that determines turbulence affecting wind plants on the spatial and temporal scales necessary for forecasting wind. Efforts are underway to leverage federal high performance computing capabilities to develop and run models that can predict complex flow and its effect on and within wind plants both locally and regionally.

An important advance in wind speed measurement capability is remote sensing technology for recording wind speed and other characteristics from the ground. The most widely used types of this technology are Doppler and scanning LIDAR,[41] which uses atmospheric scattering of beams of laser light to measure

41. *Remote sensing* technology that measures distance by illuminating a target with a *laser* and analyzing the reflected light.

profiles of the wind at a distance. For land-based wind on flat topography, comparisons between Doppler, LIDARs, and tower-based wind measurements have been so favorable that LIDARs are being considered to provide reference wind measurements for wind plant production forecasts. Industry is investigating the use of look-ahead LIDAR systems to provide data on incoming winds before they arrive at the turbine. This can provide time for turbine control systems to adjust operation to match developing winds, an innovation that can increase energy capture and reduce loads during operations. For offshore applications, buoy-mounted LIDAR systems with sophisticated correction algorithms to allow for buoy motion promise to improve the quality of data collected while avoiding the cost of building measurement towers offshore.

Future Trends—Complex Flow

Improving the fidelity of the fundamental physics in computational models of the wind will improve wind plant power forecasts, which in turn will help optimize wind plant interaction with the transmission grid. Complex flow research will reduce errors in the representation of winds and turbulence near the ground in current models. Understanding complex flow is particularly important in mountainous terrain and coastal areas. Improvements in treatment of inflow and wake flows, turbine aerodynamics, and wind turbine technology will contribute to optimization of wind plants. Continued development of models and measurement techniques will contribute to improved wind turbine technology and lower LCOE. For example, new wind measurement technologies could provide readings throughout the rotor diameter of increasingly large wind turbines. Scanning versions of turbine-mounted LIDARs are being developed to optimize control in response to variation in wind inflow. Remote sensing measurements offshore can be used to eliminate the mast required for meteorological measurements and get bankable site data to lower risk and uncertainty at the project level, lower loads in conjunction with advanced controls, and validate wind resource models. DOE's "Atmosphere to Electrons" initiative, or "A2e," is designed to comprehensively address these complex flow issues, as well as the challenges of aerodynamic interactions between wind turbines operating in close proximity to one another within a wind plant. For more information, see Section 4.2 of the *Wind Vision* roadmap.

2.5.2 Wind Plant Technology Status

The scientific principles of modern wind turbine design and operation are well understood. As described in Section 2.1, continued technical improvement has reduced wind LCOE over time. This reduction, in combination with policy support and market barrier reduction, has led to rapid growth in wind deployment in the years leading up to the *Wind Vision*. Most utility-scale turbines being installed in the United States are three-bladed machines with controllable blade pitch, variable-speed operation, and computer controls. A yaw controller uses wind direction sensors for controlling the rotation, or yaw, of the nacelle around the tower and keeps the rotor facing the wind. The controller changes the orientation of the blades (pitch) when the wind speed is high enough to produce useful power (cut-in wind speed), and the rotor begins to spin. When the wind speed exceeds the speed required for the machine to produce its full rated power (rated wind speed), the blade pitch is increased to regulate the power output and rotor speed to prevent overloading the structural components. If wind speed exceeds design limits for turbine operation, the controller shuts down the machine by further increasing blade pitch.

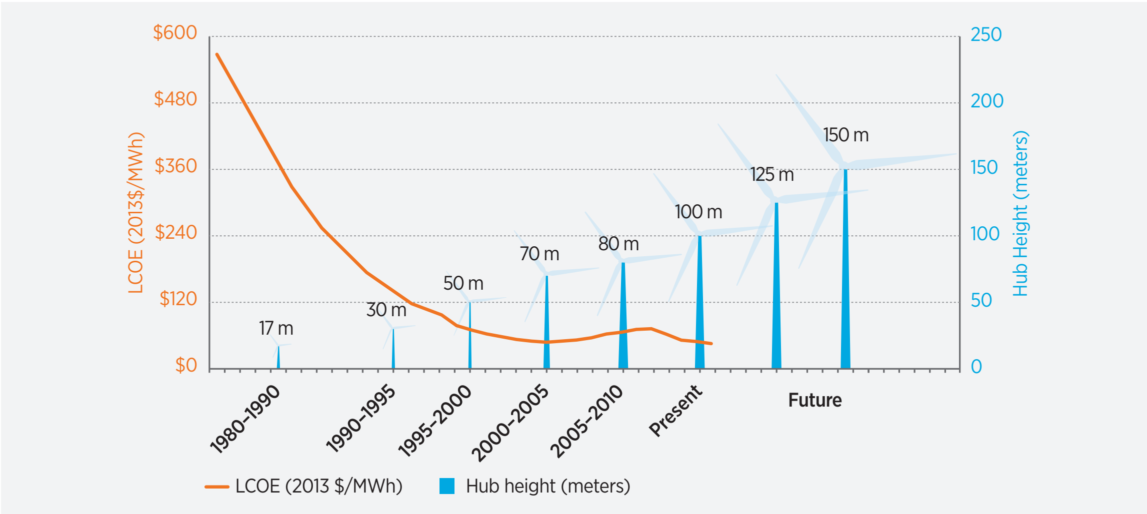
The amount of power in the wind available for extraction by the turbine increases with the cube (the third power) of wind speed; thus, a doubling of wind speed increases the available power by a factor of eight (2^3). The rotor and its associated controllers are designed to operate the turbine at the highest possible efficiency between cut-in[42] and rated wind speeds, hold the power transmitted to the drive train at the rated power when the winds go higher, and stop the machine in extreme winds. Modern utility-scale wind turbines generally extract about 50% of the available power in the wind at wind speeds below the rated wind speed, while the maximum power that a device can theoretically extract is 59% of the available power (the "Betz Limit"). Typically, a modern turbine will begin to produce power at a wind speed of 3–5 m/s and reach its rated power at 11–14 m/s. Around 25 m/s, the control system pitches the blades to stop rotation, feathering the blades to prevent overloads and protect turbine components from possible damage

42. Cut-in speed is the wind speed at which the turbine rotor begins to turn and the turbine begins to produce electricity.

due to high winds [18]. Some modern machines reduce rotational speed gradually in high winds to provide a gradual, rather than abrupt, reduction in power output as the wind speed increases.

Wind Turbine Scale-Up

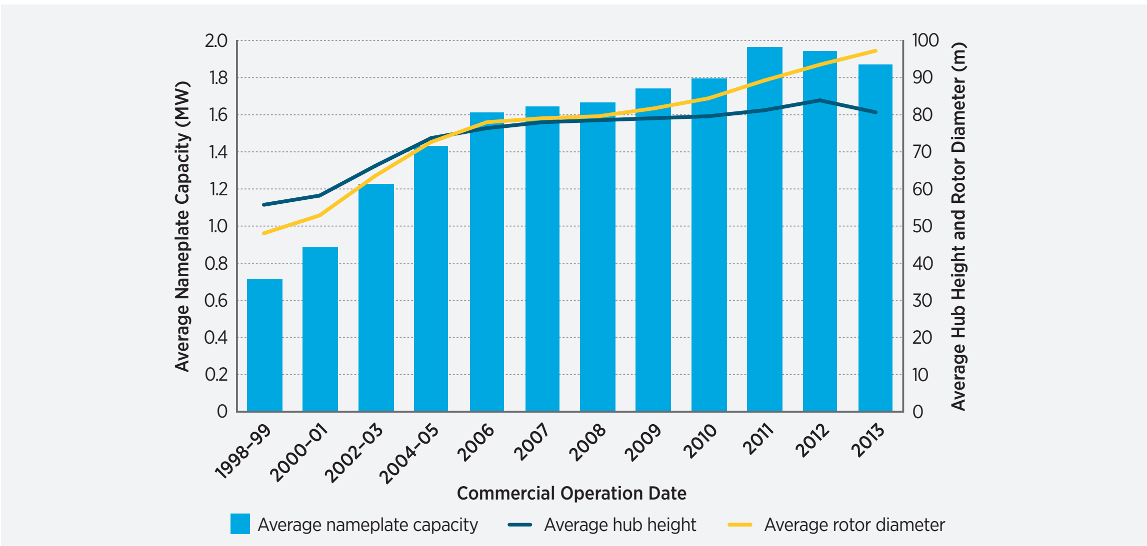
The average size and upper range of wind turbines installed in the United States has increased, with a period of rapid scale-up from 1998 to 2006 and again from 2009 to 2012 (Figure 2-26). In 2013, average nameplate capacity of utility-scale wind turbines was 1.87 MW, average rotor diameter was 97 m, and average tower hub height was 80 m [6]. Though there was a slight downtick in average hub heights from 2012 to 2013, this may be more attributable to the significantly smaller number of turbines installed in 2013 rather than an underlying trend (Figure 2-27).



Note: LCOE is estimated in good to excellent wind resource sites (typically those with average wind speeds of 7.5 m/s or higher), excluding the federal production tax credit. Hub heights reflect typical turbine model size for the time period.

Source: Wiser and Bolinger [6]

Figure 2-26. Wind technology scale-up trends and the levelized cost of electricity



Source: Wiser and Bolinger [6]

Figure 2-27. Characteristics of utility-scale land-based wind turbines 1998–2013

Low Wind Speed Technology (LWST)

The wind industry has begun deploying utility-scale projects using LWST with high hub heights and large rotors that allow greater energy capture even at sites with lower wind speeds.[43] In areas with less-energetic wind regimes, such as the Great Lakes region, the industry is installing turbines with towers taller than 100 m and rotors greater than 100 m in diameter [33, 25, 107]. LWST has become cost-effective through technical innovations in blade design and manufacture, as well as innovations in turbine controls that work to limit loads on key components. This trend in LWST is seen in General Electric's 1.5–1.8 MW wind turbines, where the rotor disc area per installed MW of generation capacity doubled between 2006 and 2013.[44] Wind turbines offered by other manufacturers show similar trends. As areas of higher wind resource are developed and constraints such as limited transmission capacity increase, the total potential developable area will become increasingly attractive for development with LWST. LWST can be used at good to excellent sites,[45] as well as at lower wind speed sites (average wind speeds of less than 7.5 m/s) such as those in the Southeast, Northeast, and portions of the West.

Tower Technology

Average hub heights for land-based turbines increased 46% from 1998 to 2013, growing from just over 55 m to 80 m. Energy capture at low wind speed and/or high wind shear sites is further facilitated by the use of tower heights of 100 m or more, which places the turbine rotors in higher average winds at most wind plants. Taller towers that reach higher winds could expand developable areas throughout the United States. The cost of towers, however, increases rapidly with increasing height, creating a trade-off between tower cost and the value of added energy production. Under current market conditions, technical innovations will be required for land-based tower heights beyond 120 m to be economical, since the installed cost increases faster than the energy production for most sites. In addition, Title 14 of the Code of Federal Regulations, Part 77, requires developers of all structures of 140 m and higher (including wind turbines) to file notice with the Federal Aviation Administration and undergo a public comment period before approval.

Rolled steel is the primary material used in wind turbine tower structures for utility-scale wind projects. Tubular steel tower sections are produced through automated manufacturing processes. Plate steel is rolled and machine-welded at the factory, then transported to and assembled at the project site.

Conventional rolled steel towers can be transported with tower sections up to 4.6 m in diameter over roads and 4.0 m via railroad. Tower diameters exceeding 4.6 m are difficult to transport. These transport restrictions result in sub-optimal tower design and increased cost for tower heights exceeding 80 m. A structurally optimized tower would have a larger base diameter, with thinner walls and less total steel. Overcoming this limitation would reduce project costs and LCOE.

New tower configurations are being evaluated to overcome transport limitations. These new configurations—known as hybrid towers—include concrete tubes for the lower, large-diameter sections and steel for the upper sections. Concrete towers have separate, pre-fabricated concrete elements with diameters up to 14.5 m. Large-diameter bottom segments can be produced as two or three partial shells that can be shipped on conventional transportation systems. Such towers could also have the concrete portions manufactured at the wind plant site. Research is also underway on fabric-covered space-frame towers that can also be assembled at the wind plant site, eliminating transportation constraints.

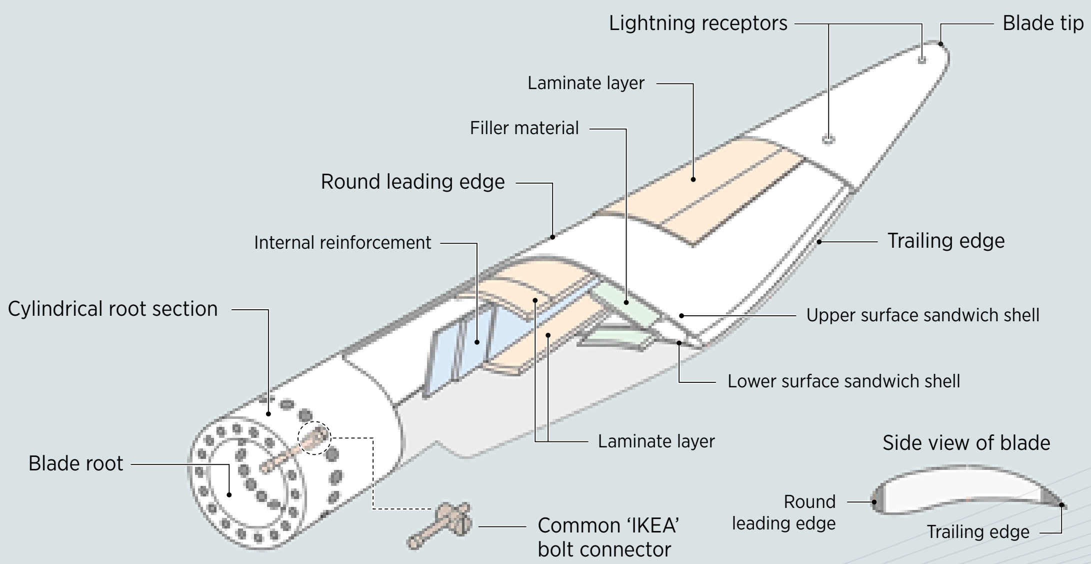
Blade Technology

Rotor blades have increased in length more rapidly than towers have grown in height, thereby increasing potential energy capture. Average land-based rotor diameters nearly doubled from 1998 to 2013, from less than 50 m to 97 m. Of the 582 turbines installed in 2013, 75% featured rotor diameters of 100 m or larger, a notable shift toward larger blades [7].

43. Annual average wind speeds as low as 6.0 m/s (13.4 miles per hour),

44. See product fact sheets at *https://renewables.gepower.com/wind-energy/turbines/full-portfolio.html*.

45. If there is no transmission available, a site may not be developable despite a high wind speed.



Source: Wind Power Monthly, July 2012

Figure 2-28. Turbine blade diagram

Optimizing LCOE through blade design involves tradeoffs between energy capture and turbine structural loads. Nearly all manufacturers have adopted full-span,[46] variable-pitch blades that regulate rotor power in high winds and reduce loads in extreme storms. Some manufacturers are moving away from blade geometries that are close to the aerodynamic optimum, sacrificing small amounts of energy capture to reduce structural loads and/or manufacturing costs and logistical constraints. The evolving designs feature much smaller maximum chord dimensions (the longest line joining the leading edge to the trailing edge) near the root of the blades. These blades are less expensive to manufacture and are easier to transport on conventional trailers or by rail. Also, reduced chords over the outer 1/3 of the blade span can significantly reduce structural loads, with only small reductions in energy capture, reducing the overall cost of energy. Reducing the outboard blade area only slightly decreases energy capture but significantly reduces structural loads and physical dimensions, resulting in manufacturing and transport cost savings. The industry is exploring rotor blades that can be delivered to a wind plant in two or more pieces and assembled on-site, which would enable the continued growth of rotor diameters.

Another advancement in blades and rotors is innovative airfoil designs to achieve specific goals, such as maximum thickness and aerodynamic performance. Airfoil sections with blunt trailing edges, known as flat back airfoils, have been deployed for the inboard region of large wind turbine blades because they provide structural advantages. Vortex generators near the root have been used to reduce the adverse effects of flow separation. Specially-designed airfoils have been developed and used near the tip to reduce noise.

Advanced materials are being used to manufacture lighter blades, including carbon fiber in structural spar caps, and sophisticated engineered cores. Other novel blade configurations are under development that use aero-elastic tailoring to alter the blade geometry in response to high-load wind conditions in a manner that reduces the loads.

The growing trend of making several blade lengths available for the same basic turbine has contributed to the lower cost of wind power. This, along with variations in the tower height, permits turbines to be customized for specific conditions at each wind plant. This approach can better optimize the trade-offs between energy capture and structural loads.

46. In a full-span configuration, the entire blade changes pitch.

Drive Train Technology

The drive train converts a rotor's rotational power into electrical power and generally includes a main shaft, a gearbox (unless a direct-drive configuration is used), a generator, and a power converter. As of 2006, most utility-scale wind turbines used a three-stage gearbox to convert the power of the rotor blades (low rotational speed, high-torque) into high-rotational-speed, low-torque power suitable for a conventional high-speed generator operating at 1,200–1,800 RPM [108]. By 2013, most utility-scale turbines used variable-speed technology. Variable-speed turbines can extract more energy at low wind speeds and impose lower structural loads at higher wind speeds than constant speed generators. In variable-speed turbines, rotor speed is controlled using blade pitch and power electronics to alter the frequency of the generator field.

Continued advancements in drive train technology can decrease maintenance and related costs, which will in turn reduce LCOE. Additional drive train technology developments since 2006 include:

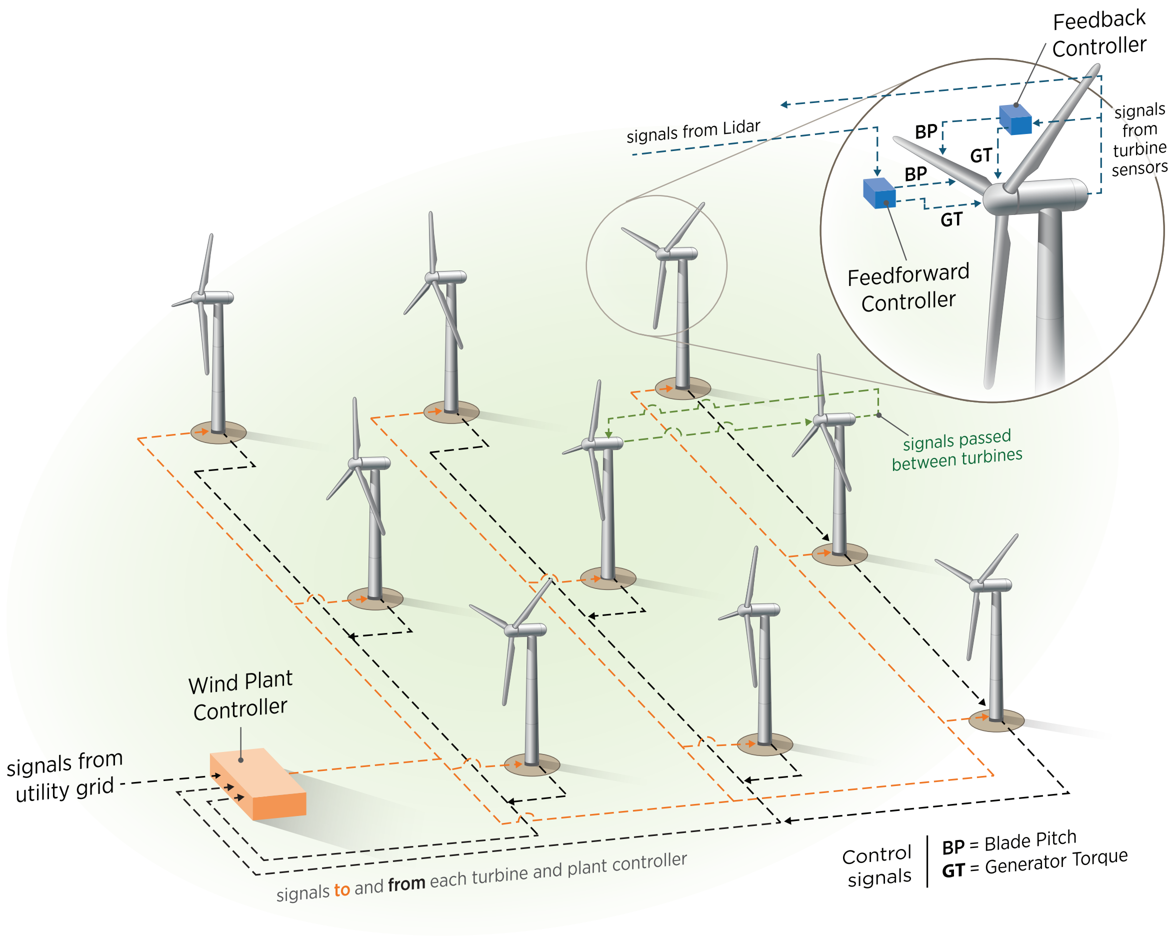
- **Direct drive** generators that eliminate the need for a gearbox. Direct drive turbines comprised 3.3% of new U.S. capacity installed in 2012 (194 turbines totaling 429.7 MW), an increase from 17 direct drive turbines installed in 2011 (totaling 35.3 MW) and no more than three such turbines per year from 2008 to 2010. Direct drive technology has been relatively slow to enter the U.S. market in comparison to global trends—28% of global wind turbine supply in 2013 featured direct drive turbines [6].
- **Permanent magnet** synchronous generators with improved efficiency based on rare-earth materials. These generators are used in conjunction with high-speed gearbox designs as well as direct-drive, gearbox-free turbines.
- **Medium-speed** single-stage drive trains with generators operating at approximately 100 RPM.
- **Main shafts** with dual bearings or a non-rotating kingpin to support the hub and isolate the gearbox from rotor loads.
- **Full power conversion** technologies that increase the range of variable rotor speeds, further improving energy capture at low wind speeds.

Control Technology

Wind plants consist of large arrays of wind turbines connected through a single point to the transmission grid. Controls for wind turbine speed, power output, and other characteristics, however, have been used largely for individual machines in response to turbine-based criteria. These controls allow operators to manage and monitor turbines remotely, from the site's O&M station as well as from regional and global remote operating centers. More advanced control technology now includes active controls to sense turbulence-induced rotor loads and alter turbine operation to reduce these loads (Figure 2-29). Controlling all turbines within the plant to maximize total production and reduce loads could result in lower LCOE.

Wind turbine controllers integrate signals from dozens of sensors on or around the turbine to control rotor speed, blade pitch angle, generator torque, and power conversion voltage and phase. The controller manages critical safety measures, such as shutting down the turbine when extreme conditions are encountered. Electrical controls combined with power electronics enable turbines to deliver fault ride-through operation, voltage control, and volt-ampere-reactive support to the grid. As with other ancillary services and providers, the necessary incentives must be in place to encourage this flexibility. Research is underway on wind turbine active power controls and market incentives necessary to induce the provision of these flexibility services when they are cost-effective. Active power control allows the power system operator to control the wind generator output when there is excess energy or when fast response is required to maintain reliability.

Advancements in individual turbine sensor technology include built-in condition monitoring systems that measure vibrations or oil particle count in key areas of the drive train. The vibrations are tracked continuously. When the signature of the vibration changes, a notice of non-standard operating conditions is sent to operators, allowing them to take precautionary measures such as shutting down a turbine until inspection and repair can occur. Condition monitoring systems have enabled operators to make proactive minor repairs up-tower without a crane before failure of one component affects others, reducing costs and downtime.



Source: National Renewable Energy Laboratory

Figure 2-29. Wind plant controls, including LIDAR sensor signals for feed-forward control and integrated wind plant control

Advanced controls have improved turbine and wind plant performance and reliability. Such controls also offer some of the best opportunities for reducing LCOE. Advanced turbine controllers can accommodate larger rotors and increased energy capture for a given drive train without changing the balance-of-system requirements. Several approaches are used, including model-based control; multiple-input, multiple-out systems; and micro-tuning of turbine controls for specific wind plant sites. These advanced methods are often used with passive load reduction technologies developed for longer rotor blades.

Individual blade pitch control is another advanced control scheme. While collective pitch control adjusts the pitch of all rotor blades to the same angle, individual blade pitch control dynamically and individually adjusts the pitch of each rotor blade in real-time based on measured loads. The main benefit of individual blade pitch control is the reduction of fatigue loads on the rotor blades, the hub, and mainframe and tower structures. In order to reduce these loads, especially asymmetric loads caused by heterogeneous wind fields, the pitch of each rotor blade has to be adjusted independently from the other blades. A reduction of fatigue loads has two considerable advantages: it allows lighter designs and can translate into increased reliability [109]. Individual blade pitch control systems are currently in service on some modern turbines. The innovation permits higher wind conversion efficiency, which translates to lower LCOE for wind power.

Research is also underway to develop plant-wide controls to optimize overall wind plant output. This innovation presents the opportunity to improve overall plant-level energy capture and reduce structural loads by operating the wind turbines in an integrated fashion. Another way controls can contribute to wind deployment is by using active power control of the entire wind plant in a way that improves overall grid stability and frequency response and regulation. Active power control helps balance load with generation at various times, avoiding erroneous power flows, involuntary load shedding, and machine damage. This technology, discussed in more detail in Section 2.7, could change the paradigm for the integration of wind turbines onto the transmission grid [110], further expanding deployment opportunities.

Future Trends—Plant Technology

Continued advancements in wind power technology will drive reductions in LCOE and facilitate wind deployment in new markets, such as low wind speed areas. Some key on-going trends include:

- **Towers:** Transportation, logistical, and regulatory issues must be addressed in order to deploy taller towers to enhance wind resource access. On-site manufacture or assembly of towers provides a key opportunity. As previously discussed, all structures higher than 140 m (including wind turbines) must file notice with the Federal Aviation Administration and undergo a public comment period before approval.
- **Blades:** The development of efficient multi-piece blades that can be economically transported to new wind plants will enable further growth in rotor diameters. The development of low-cost carbon fiber material systems will play a key role in the design and manufacture of these larger rotors.
- **Drive trains:** Increasing diversity in drive train configuration—including geared, medium-speed and direct-drive technologies—is expected to continue. Drive train configurations are expected to have increased reliability and service life, and greater overall efficiency. Power electronics systems will provide increasingly valuable grid services, such as frequency regulation and synthetic inertia.
- **Controls:** Given current technology trends, wind plants will increasingly be controlled and operated as an integrated system, enhancing reliability and energy capture, and improving grid stability. Innovations in turbine-level control systems, such as feed-forward control, will continue to enable increases in rotor size without commensurate increases in structural loads. Research will continue on wind turbine active power controls and the market incentives necessary to induce the provision of these services (i.e., when they are cost effective).

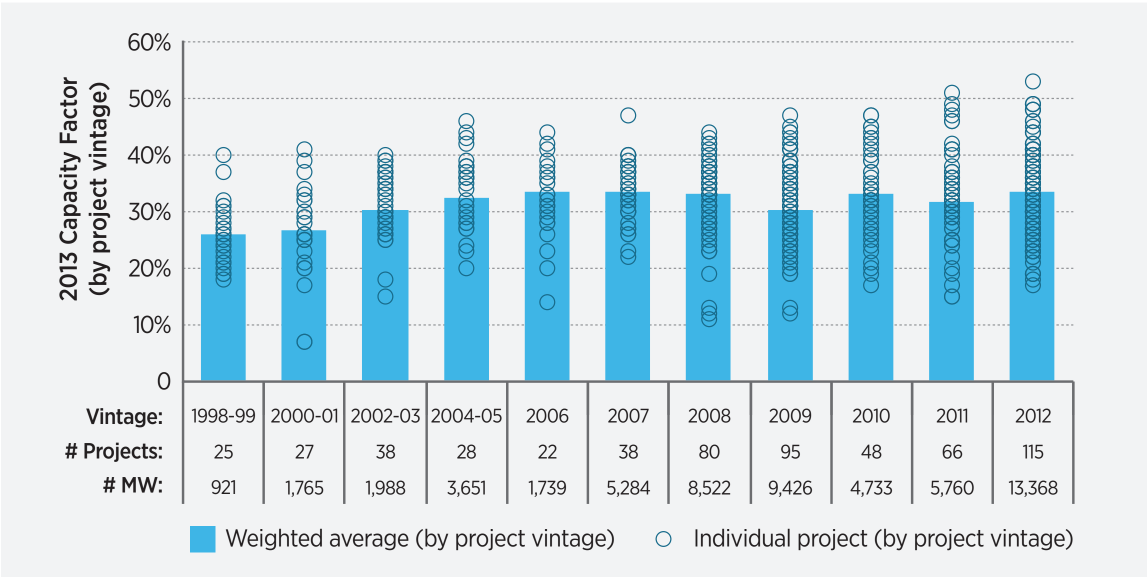
2.5.3 Wind Plant Performance and Reliability

Cost drivers for LCOE include wind turbine and wind plant performance, as measured by annual energy production and capacity factor. Wind turbine reliability in terms of scheduled and unscheduled O&M and component replacement is also an LCOE driver, and improvements offer opportunity for reductions in LCOE and technical risk.

Capacity Factor

As noted, capacity factor is a measure of the productivity of a power plant. It is calculated as the amount of energy that the plant *actually* produces over a set time period divided by the amount of energy that *would have been* produced if the plant had been running at full capacity during that same time interval. Wind project capacity factors have been higher on average in more recent years (e.g., 32.1% from 2006 to 2013, versus 30.3% from 2000 to 2005). Time-sensitive influences—such as inter-year variations in the strength of the wind resource or changes in the amount of wind power curtailment—may mask the positive influence of turbine scale-up on capacity factors in recent years [6].

Variations by project vintage year occur due to countervailing trends of larger rotor diameter, which tends to increase capacity factor, and increasing installations in lower wind resource sites, which tends to reduce capacity factor. These trends have overshadowed the potentially large positive effect of technology improvements such as larger rotors, taller towers, and sophisticated controls on capacity factors. As shown in Figure 2-30, a few outlying individual projects show capacity factors above 40%, with a few exceeding 50% [6]. Variances in capacity factor can be influenced by:



Note: Sample includes 582 projects totaling 57.2 GW

Source: Wiser and Bolinger [6]

Figure 2-30. Wind project capacity-weighted average capacity factors for 2013 by commercial operation date for project vintages 1998–2012

- **Regional Differences:** Design changes such as larger rotors and taller towers can open new resource areas to utility-scale wind projects with capacity factors sufficient for cost-effective development. Data indicate average regional capacity factors for utility-scale wind projects built in 2012 were highest in the U.S. Interior (38%), and lowest in the West (26%). These regional differences can be explained by differences in wind resources and by varying types of deployed wind turbine technology. A lower specific power rating[47] for a turbine yields a higher turbine capacity factor. For turbines installed 2011 to 2013, 30% of all turbines installed in the Great Lakes region had a specific power rating less than 220 watts per square meter (W/m^2), vs. 5% of the turbines in the Western region.
- **Curtailment:** National wind power production can be reduced by curtailment, where the dispatch order from the transmission system operator to the wind plant is to reduce or stop generation even though the wind resource is available. Some reasons for curtailment, such as transmission constraints, are discussed in Section 2.7. Operators may also voluntarily curtail production in response to price changes. The United States has many balancing areas,[48] each of which may have its own curtailment practices. Though curtailment varies by balancing area, in aggregate curtailment has declined to 2.5% of total wind power generation in 2013, down from a peak high of 9.7% in 2009. Specifically, only 1.2% of potential wind power generation within the Electric Reliability Council of Texas (ERCOT) was curtailed in 2013, down sharply from 17% in 2009, roughly 8% in both 2010 and 2011, and nearly 4% in 2012. Primary causes for the decrease were the Competitive Renewable Energy Zone transmission line upgrades and a move to more-efficient wholesale electric market designs [6].

47. The “specific power” of a wind turbine is the ratio of generator nameplate capacity (in watts) to the rotor-swept area (in m^2). With growth in average swept area outpacing growth in average nameplate capacity, there has been a decline in the average specific power (in W/m^2) among the U.S. turbine fleet over time, from around 400 W/m^2 among projects installed from 1998–2001 to 253 W/m^2 among projects installed in 2013.

48. A balancing area is a predefined area within an interconnected transmission grid where a utility, an independent system operator, or a transmissions system operator must balance load (electrical demand) and electrical generation while maintaining system reliability and continuing interchanges with adjoining balancing areas. An interconnected grid can have one or many balancing areas. For example, the Western Interconnection, which covers much of the western U.S. and western Canada, has 35 balancing areas, while the Texas Interconnection only has one.

Wind Turbine System Reliability

Relative to capacity factor, turbine downtime has a relatively smaller impact on LCOE, with availability rates[49] of greater than 98% as of 2013 [25]. Replacement of failed components can cost hundreds of thousands of dollars, due to the cost of the components as well as the rental costs of large cranes, and can result in lost revenue from lost production time. European WindStats data from 2008 to 2012 show a decrease in turbine downtime due to gearbox, electric system, and generator failures, but an increase due to rotor failures [111]. Separately, the European Reliawind project found electrical systems, pitch systems, and yaw systems to be the largest drivers of turbine downtime [112]. One of the challenges in understanding trends in component failures is that turbine reliability is affected by many factors including equipment quality, operating conditions and maintenance, and the age of turbines. Improving wind turbine component, sub-system, and system reliability can reduce costs for O&M and replacement of components, as well as reducing downtime. Better tools have been developed to predict remaining useful component life and verify the accuracy of the prediction of fatigue life for new turbines.

Table 2-5. Aggregated Utility-Scale Wind Turbine Downtime by Turbine Subsystem for 2007 and 2012

Downtime by Subsystem (%)	2007	2012	Variation from 2007 to 2012
Subsystems with Decreasing Downtime Trends			
Gearbox	30.9	9.9	-21.0
Electric system	15.7	6.4	-9.3
Generator	13.2	4.3	-8.9
Pitch adjustment	9.9	1.8	-8.1
Main shaft/bearing	6.7	5.8	-0.9
Hydraulics	5.8	3.1	-2.7
Air brake	5.5	1.8	-3.7
Sensors	2.4	1.8	-0.6
Mechanical brake	0.8	0.1	-0.7
Subsystems with Increasing Downtime Trends			
Electric controls	4.5	5.2	0.7
Rotor	2.9	6.1	3.2
Yaw system	1.6	5.6	4.0
Windvane/anemometer	0.1	1.0	0.9
TOTAL	**100**	**52.9**	**-47.1**

Note: Total turbine downtime in 2012 was 47.1% less than turbine downtime in 2007. Changes in 2012 total turbine and subsystem downtime are measured as a percentage of the 2007 total turbine downtime.

Source: National Renewable Energy Laboratory and Wind Stats, data from 2007 to 2012

49. The availability factor of a *power plant* is the amount of time that the plant is able to produce *electricity*, divided by the amount of time in the period.

Gearbox Reliability

A 2013 summary of insurance claims revealed that the average total cost of a gearbox failure was $380,000 [113]. An analysis of 1000 turbines over a 10-year period reported that 5% of turbines per year required a gearbox replacement [29]. Gearbox reliability remains a challenge for utility-scale wind turbines, though trends in Table 2-5 indicate that reliability has improved since 2007. The industry uses a systems approach as the most effective for improving this aspect, with attention to reliability integrated throughout the design, manufacturing, commissioning, and O&M stages [114]. Through collaborations, diagnostics, and accelerated testing, the industry has gained a better understanding of the most frequent gearbox failure modes and possible root causes. Researchers have confirmed that a key factor contributing to premature gearbox failures is that bending loads (rather than torque loads) on the input shaft cause excessive loads on the gears and bearings. Tapered roller bearings have been incorporated into the planetary design, and new main bearing and main shaft design strategies have been adopted to reduce non-torque loads transmitted to the gearbox. It has become standard practice to perform extensive dynamometer testing of new gearbox configurations to prove durability and reliability before introduction into serial production [18]. Such dynamometer tests have identified design or material weaknesses that were remedied before field testing or production.

Condition monitoring systems mounted on parts of the drive train are becoming more common, enabling detection of problems earlier and minimizing downtime. Gearbox repairs or part replacements are more often performed up-tower. This avoids the need for a crane to lower components to the ground, thereby reducing maintenance costs. Refinements in materials, quality, metallurgy, surface finishing, and lubricants are all considered in efforts to improve gearbox reliability.

Generator Reliability

A generator failure in 2013 was estimated to cost $310,000 [113], while an estimated 3.5% of turbines required a generator replacement [29]. Data from U.S. wind plants reveal that electrical winding and bearing failures are the two largest sources of downtime for generators. Electrical winding failures result from a combination of improper specification and design issues, manufacturing inconsistency, or quality issues. Environmental conditions and poor electrical power quality exacerbate generator reliability problems. Bearing failure is the single largest contributor to generator unreliability and is probably influenced by multiple mechanical root causes: improper lubrication, machine misalignment, and transient electrical current damage [115]. Original equipment manufacturers have pursued direct drive turbines to avoid misalignment problems, but to date there have been no published studies in the United States to confirm improved reliability and lower operating costs of direct drive turbines. Generator manufacturers often make upgrades and revisions to address identifiable failure modes. These changes might include cooling system improvements, bearing design changes, and other insulation and structural improvements based on the results of electrical and mechanical testing.

Rotor Reliability

Average replacement costs for a blade failure are estimated at $240,000 [113], with 2% of turbines requiring blade replacements annually [29]. With larger blades being used on wind turbines, weight and aeroelastic limitations have put added pressure on blade design and manufacturing, which may be one of the explanations for the uptick in rotor-driven downtime reported in Table 2-5. Blade failure can arise from manufacturing and design flaws, transportation, and operational damage. Manufacturing flaws include fiber misalignment, porosity, and poor bonding. During transport from the manufacturing plant to the wind plant site, blades can undergo several lifts, which result in localized loads that can cause damage if not properly executed. Operational damage is primarily related to either lightning strikes or erosion of blade leading edges.

Testing of composite material coupons and sub-structures to determine the effect of manufacturing defects has increased both in research and industry [116]. Manufacturers increasingly use non-destructive inspection[50] practices to assess the quality of blade structures, especially critical sections like spar caps. Non-destructive inspection techniques have been found effective in finding several common defects, including dry spots, delaminations, and gaps in adhesive bonds. Improvement in inspection and repair techniques, coupled with the high cost of blade replacement, has led the industry to move towards repairing damaged blades. The development

50. Non-destructive inspection uses techniques that do not cause harm when evaluating materials, components, or systems.

of in-situ blade inspection technology and processes could become an alternative to manual inspections, improving reliability and technician safety. Ultimate-load and fatigue testing of full-scale blades are standard and required for design certification, with continuous improvement in load calculation and testing methods. The international blade design standard, IEC 61400-5, will outline in more detail what is needed to design and maintain blades for reliability. Blade testing, whether at government or private laboratories, is critical to design blades to meet expected lifetimes, because it can diagnose design or manufacturing errors which cause early and sometimes catastrophic failures. Blade test methods are continuously improving, as are design methods and manufacturing processes. For more information about testing, please see Appendix F, Testing Facilities.

2.5.4 Aftermarket Upgrades and Repowering

Most original equipment manufacturers offer aftermarket upgrades to improve wind turbine and wind plant performance of installed fleets. Some example upgrade products include modifications to turbine control parameters that allow an increase in maximum power output; vortex generators, which use small fins to optimize air flow over the blades and improve aerodynamics; and software improvements that support self-diagnosis of subsystem components and increase turbine availability. These aftermarket products are added to existing equipment to improve performance, but do not extend the useful life of the original turbine.

Repowering wind turbines occurs when equipment at a wind plant is replaced with newer, higher-performing turbines that increase the capacity factor using technologies not available when the original plant was constructed. A wind plant is typically repowered at the end of its useful life, and most original equipment manufacturers certify turbines for a 20-year lifetime. The significant increase in wind turbine power ratings since the early 1990s creates a financial incentive to repower high quality wind resource sites with new turbines. This incentive needs to be balanced against site-specific requirements in updating the balance of system elements such as the roads, foundations and potentially the grid connection equipment.

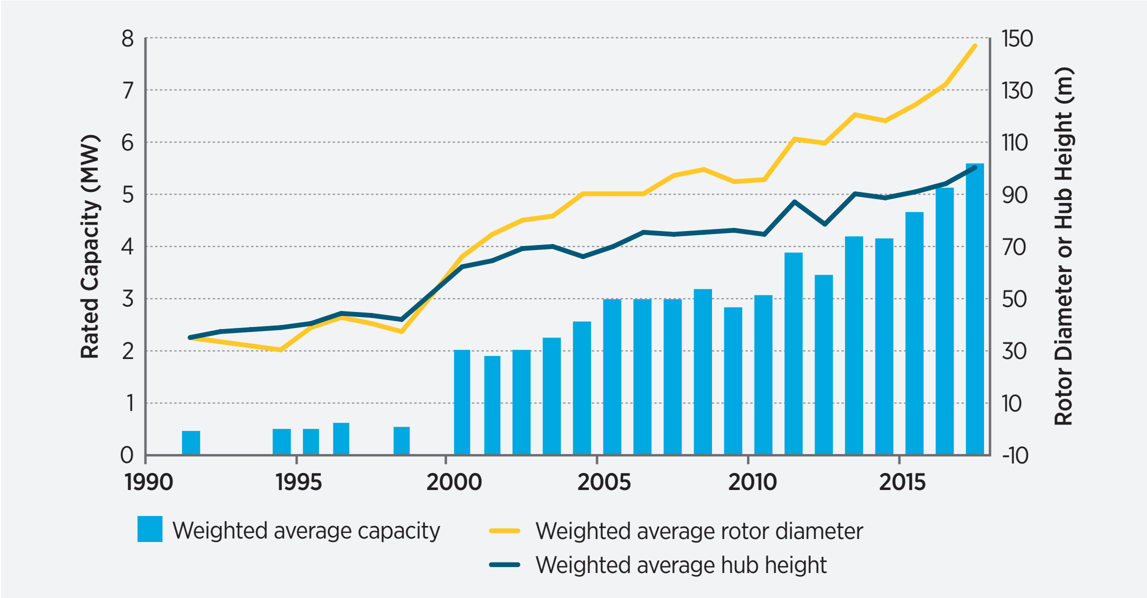
As of 2012, 75% of installed wind plant capacity (52% of installed turbines) was less than five years old, and 8% of installed capacity (34% of installed turbines) was older than 10 years [117]. As these installed assets age, the market for repair, replacement and repowering grows. While regulatory issues in California in the early 2000s prevented significant repowering activities, new policies have improved the repowering market. See Section 3.3.1, Capacity Additions, in Chapter 3 for more information.

2.5.5 Offshore Technology

Offshore wind technology can take advantage of many of the same technology developments described for land-based systems. These areas include array optimization strategies, turbine architectures, advanced composites, aerodynamics, and controls. There are many technology areas, however, in which offshore wind technology is progressing along unique pathways independent of land-based drivers. Offshore wind turbines

- are trending toward larger turbines twice the size of their land-based counterparts;
- demand higher reliability due to vastly more challenging accessibility;
- rely on subsea power cable networks and substations far from land; experience significant hydrodynamic loading; and
- are coupled to a range of support structures, including floating systems that are highly dependent on water depth.

New technology is expected to contribute to offshore wind cost reductions, which can be realized through lowering capital cost, increasing energy production, increasing reliability, and lowering the risk profile for investors. The turbine comprises just 30% of the total capital cost of an offshore wind project, while the balance of system and associated project construction costs represent the remainder [118]. A major technology trend since 2008 has been to develop larger, 5–7 MW capacity turbines. These larger turbines enable greater balance of system cost reductions (foundations and marine construction) on a per MW basis because they allow for fewer foundations, less cable, lower O&M, and more MW per unit area. Most major offshore turbine suppliers are developing larger turbine models specifically for offshore. These turbines



Source: National Renewable Energy Laboratory

Figure 2-31. Average turbine size, rotor size, and hub height for commercial offshore wind plants

are entering the market as prototypes or as early stage commercial production units. Transportation and erection restrictions limit the use of these turbines in land-based applications, so their introduction has resulted in new supply chains unique to offshore wind, especially for components like large blades and nacelles. Figure 2-31 shows the historic and projected average turbine size, rotor size, and hub height for installed offshore wind projects.[51] Projections are based on projects approved as of 2013.

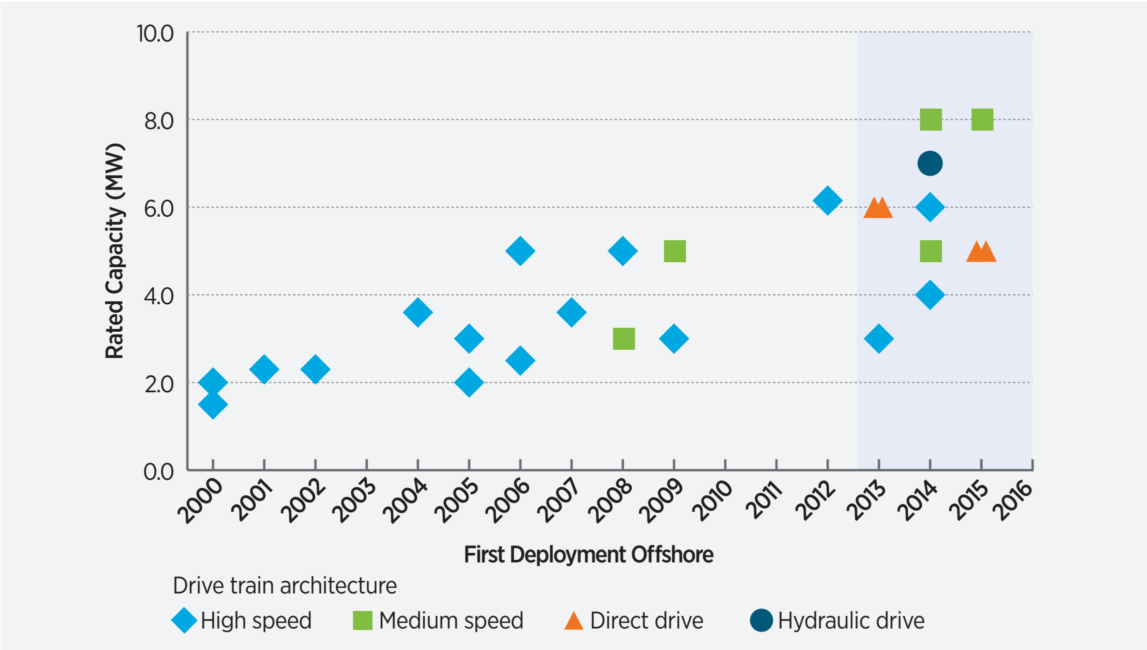
The introduction of larger turbines in European waters has also stimulated the development globally of vessels, equipment, and infrastructure with the capability to install these machines. These new vessels require cranes with maximum lift heights approaching 130 m and lifting capacities between 600 and 1,200 tons, suitable for larger turbine models [119].

This emerging fleet of offshore wind turbines is also characterized by a move toward gearless direct drive generators and single-stage geared systems with medium-speed generators (Figure 2-32). These direct-drive and medium-speed generators take advantage of innovative technologies in rare earth permanent magnets that allow lighter nacelle weights, created with lower fabrication and maintenance costs in mind. Design innovations under development include modularity of the generator poles, superconductivity, switched-reluctance, and power conversion incorporated into generator modules. New designs have demonstrated a reduction in top mass, thereby reducing weight of all support components.

Direct-drive generator technologies could be favored more in offshore applications because they reduce the total part count, which theoretically could lower offshore maintenance costs. Since offshore wind turbines are remote and accessibility is limited by weather and high vessel costs, offshore wind maintenance strategies also place a higher emphasis on remote sensing, condition monitoring, and optimizing weather windows.

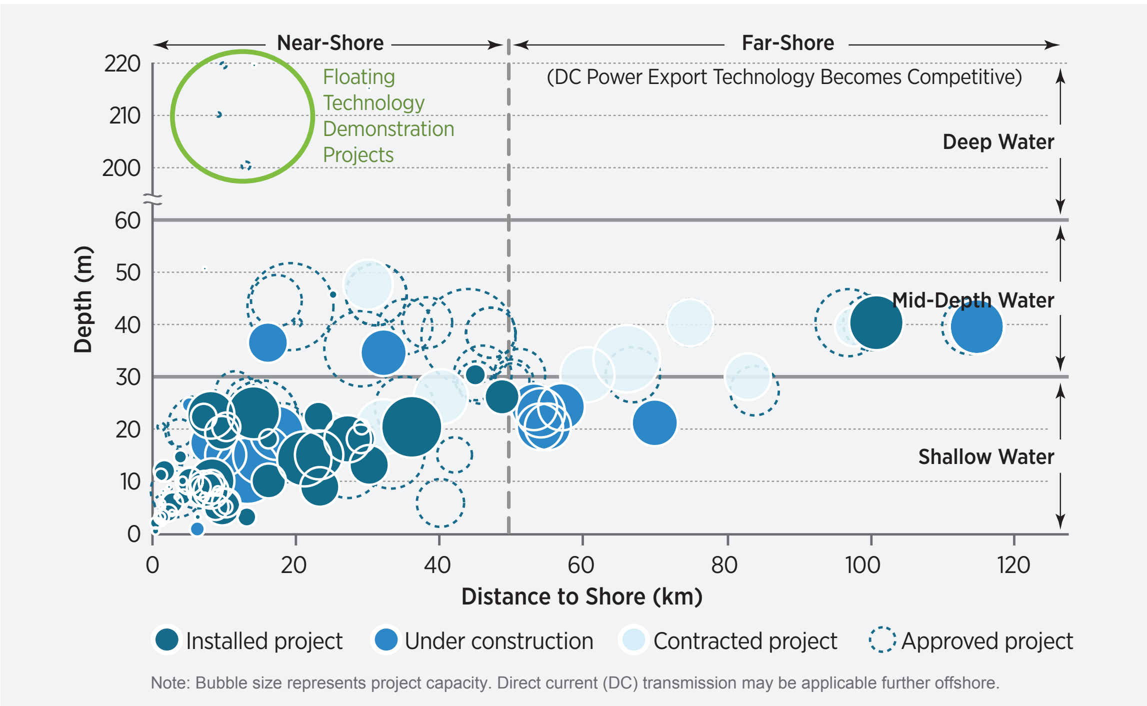
The continued rapid growth of offshore wind turbine capacity since 2008 has resulted in a commensurate growth in rotor diameter. These new offshore turbines comprise rotors up to 165 m in diameter, with blade lengths up to 80 m in length. Blades of this length challenge the 2013 state-of-the-art composite fabrication facilities and require special attention to ship blades to the project site. Blade designers have

51. The data in this figure and most data discussed in this section rely on data from deployed offshore turbines outside the U.S. since there are currently no utility-scale offshore wind projects operating in the U.S.



Source: National Renewable Energy Laboratory

Figure 2-32. Technology trends in offshore wind turbines, 2000–2016

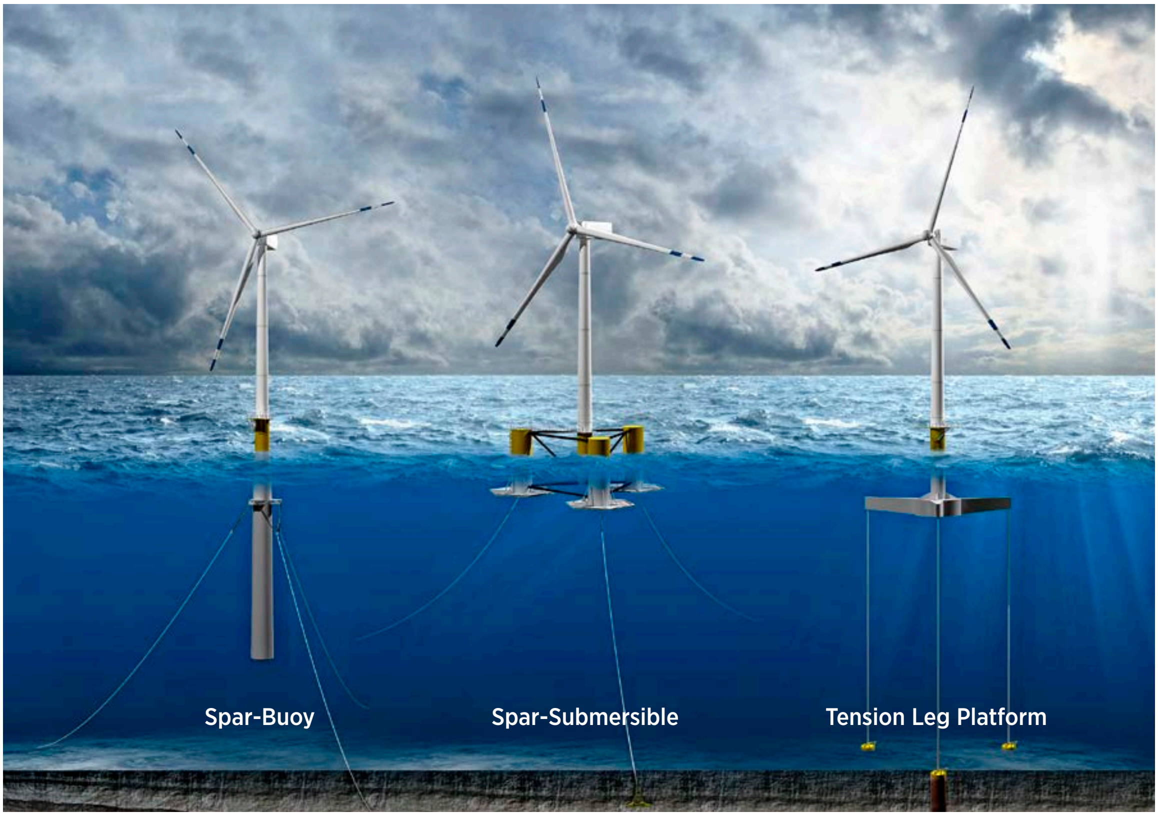


Source: National Renewable Energy Laboratory

Figure 2-33. Characteristics of offshore wind projects in Europe, 2013 increasingly moved to lighter weight materials such as industrial carbon fiber laminates, modular prepreg members, and automated fiber placement production technologies to achieve longer, stiffer blades. As of 2013, all utility-scale offshore wind turbines are designed to operate upwind of the tower, except for the Hitachi 2 MW downwind machine. There are several of these Hitachi units operating in Japan, including two floating turbines: one at Kabashima, Japan [120] and another deployed in phase 1 of the Fukushima Forward floating offshore wind project. Further development of larger machines may lead to more downwind turbine designs for offshore wind. Extreme blade lengths may deflect beyond practical upwind rotor limits, while low frequency noise concerns that restrict downwind turbines on land are less likely to be a factor in an offshore environment.

Water depth is a strong design driver in offshore wind technology development. In 2008, all installations were in shallow water less than 30 m deep, except for a 45-m deep demonstration project in the Beatrice fields off Scotland (developed by Talisman Energy). These installations were completed using conventional jack-up barge cranes on monopole or gravity-based substructures. In 2014, much of the development was mid-depth sites that are further from shore and require multi-pile substructures such as jackets and tripods. The costs increase as turbines are placed in deeper waters but conflicts with the environment and competing human use are likely to be lower [55]. Figure 2-33 shows the relationship between project depth, distance from shore, and project size over the life of the industry.

Some large-scale deployments in Europe aggregate the wind plant electrical distribution systems from multiple wind projects to facilitate efficient power delivery to shore. Some projects have implemented multi-point high-voltage direct current transmission systems for long-distance transmission of power to shore, a trend which may continue as larger facilities



Source: National Renewable Energy Laboratory. Illustration by Joshua Bauer, NREL.

Figure 2-34. Illustrations of three classes of floating wind turbine technology continue to be built further from shore. Electrical transmission backbones such as these have already been proposed in the United States in advance of offshore wind construction [121].

The trend toward deeper water has also created interest in floating wind technology (see Figure 2-34). In 2009, the first utility-scale floating wind turbine was deployed by Statoil off the coast of Norway. The turbine was named Hywind I and used a 2.3-MW Siemens turbine on a floating spar substructure. Other technology demonstration projects have since launched in Portugal [122], Japan [123], and in the first U.S. offshore wind turbine at the University of Maine [124]. Additional full-scale demonstration projects are also underway [125].

Although not yet commercially proven, floating technology could play a key role in offshore wind, especially in the United States where more than 60% of the offshore wind resource lies over water with depths of more than 60 m. In those areas, floating systems may have an economic advantage over fixed structures. The potential advantage is that floating systems at large production scale may be able to deliver lower system cost through efficiencies gained in mass production and the elimination of expensive at-sea construction steps. As of 2013, floating wind technology developers are demonstrating floating concepts with proven fixed-bottom offshore wind turbine designs.

Hurricanes pose a significant challenge to offshore wind turbines in areas where major tropical cyclone events regularly occur. This includes the U.S. Atlantic, Gulf of Mexico, and parts of the Pacific. In 2008, hurricane turbine ride-through designs were not yet being discussed, and the Minerals Management Service (now BOEM) was concerned about consistency and interpretation of the various standards [126, 127, 128]. Many developers were hesitant to consider hurricane-vulnerable sites as viable at all. As of 2014, hurricane-tolerant offshore wind design is discussed widely in international standards development organizations, with progress toward robust strategies. Turbine survivability under extreme ice loading has been demonstrated in the Baltic Sea, especially in Finland where ice conditions exceed extreme Great Lakes conditions on an annual basis [129]. These advancements in hurricane and ice load tolerance are important to expand developable opportunities for offshore wind.

2.5.6 Conclusions

Wind technology advancements, performance improvements, and cost reductions have exceeded levels viewed as aggressive in 2007 and 2008. Wind turbine technology continues to progress toward larger turbines with higher nameplate capacity, and industry is gaining increased understanding of ways to improve reliability. Manufacturers of offshore technology can leverage many of the same enhancements as in land-based wind technology, but there will also be unique design issues for offshore. Numerous actions and advancements in wind plant technology, performance, reliability, and safety are needed to continue recent trends and achieve the deployment levels in the *Wind Vision Study Scenario*. Section 4.2 discusses several *Wind Vision* roadmap actions regarding wind plant technology advancement, while Section 4.4 reviews the wind power performance, reliability, and safety roadmap actions.

Wind plant technology advancement actions in the *Wind Vision* roadmap include:

- Developing next-generation wind plant technology for rotors, controls, drive trains, towers, and offshore foundations for continued improvements in wind plant performance and scale-up of turbine technology;
- Updating design standards and certification processes using validated simulation tools to enable more flexibility in application and reduce overall costs;
- Developing and validating a comprehensive suite of engineering, simulation, and physics-based tools that enable the design, analysis and certification of advanced wind plants. Improving simulation tool accuracy, flexibility, and ability to handle innovative new concepts;
- Developing and sustaining world-class testing facilities to support industry needs and continued innovation; and
- Developing revolutionary wind power systems by investing R&D into high-risk, potentially high-reward technology innovations.

The *Wind Vision* roadmap addresses wind power performance, reliability, and safety with actions to:

- Increase reliability by reducing unplanned maintenance through better design and testing of components, and through the adoption of condition monitoring systems and maintenance;
- Develop a world-class database on wind plant operation under normal operating conditions by collecting wind turbine performance and reliability data from wind plants to improve energy production and reliability under normal operating conditions;
- Ensure reliable operation in severe operating environments by collecting data, developing testing methods, and improving standards;
- Develop and promote best practices in operations and maintenance strategies and procedures for safe, optimized operations at wind plants; and
- Develop aftermarket upgrades to existing wind plants and establish a body of knowledge and research on best practices for wind plant repowering and decommissioning.

2.6 Supply Chain, Manufacturing, and Logistics

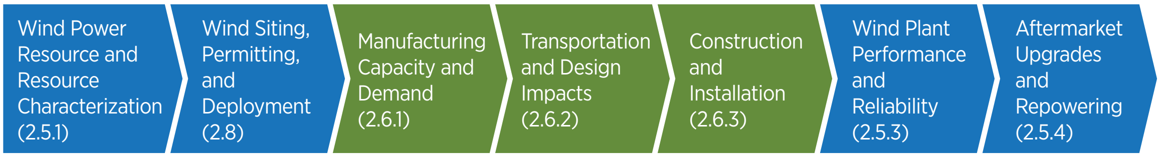


Figure 2-35. Elements of the U.S. wind power supply chain mapped to sections in this report

The U.S. wind industry supply chain comprises a range of companies spanning the life cycle of a wind plant, from initial resource assessments through long-term operation. The focus of this section is on the manufacturing, transportation, and construction portion of the supply chain, with other areas addressed throughout this report as indicated in Figure 2-35.

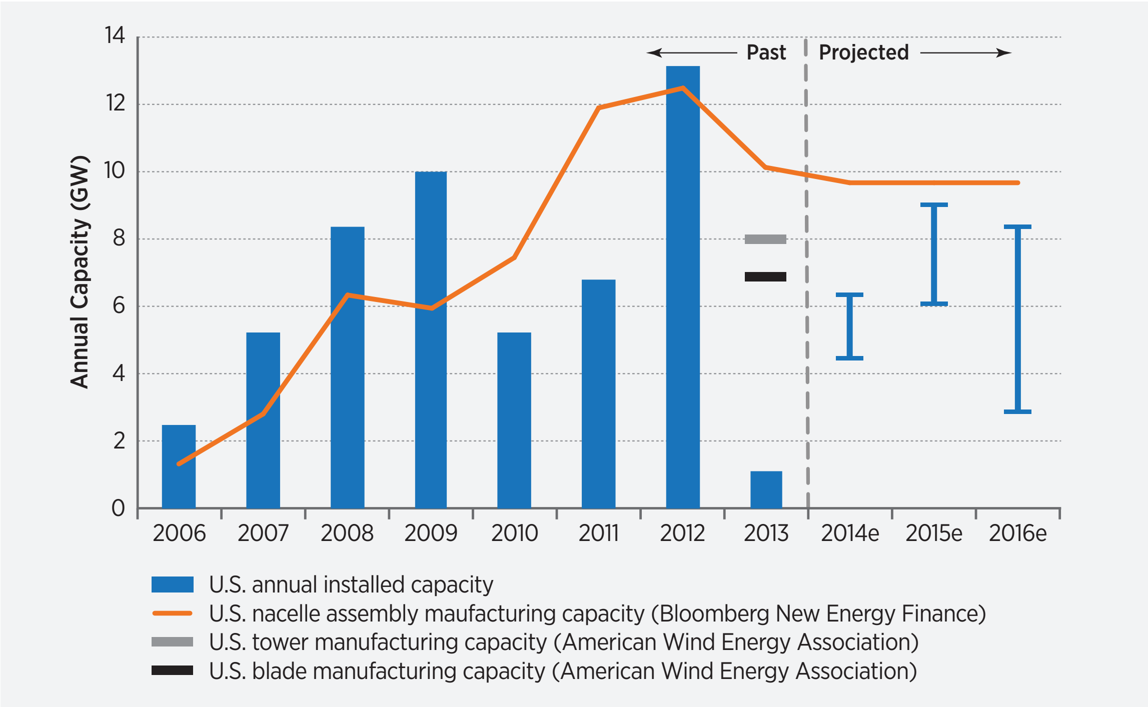
With historical domestic demand stability, wind manufacturing has moved toward higher U.S. domestic content. Unstable future demand may erode the domestic supply chain.

The U.S. manufacturing supply chain includes at least 560 companies, in more than 43 states, that process raw materials and manufacture and assemble wind turbine components [7]. The overall share of domestically manufactured turbines and components has increased over the last decade, leading to a decrease in share of imported wind turbines and select components despite record installations and industry growth [25]. Turbine technology has scaled up as well, increasing the size of components such as blades and towers, making transportation more costly and complex, and domestic manufacturing more likely. These trends helped support more than 80,700 domestic jobs across the supply chain by the end of 2012, including more than 25,500 in manufacturing (see Section 2.4.3 Workforce). With the market uncertainty created by the expiration of the PTC in 2013, employment in the U.S. wind industry contracted to 50,500 full-time equivalents across the supply chain—17,400 in the manufacturing sector—by the end of 2013 [7].

Manufacturing capacity and demand, including domestic content and international trade, raw materials, and repair and remanufacturing are summarized in 2.6.1. Section 2.6.2 covers the transportation logistics and design impacts, while Section 2.6.3 discusses installation issues.

2.6.1 Manufacturing Capacity and Demand

U.S. manufacturers have responded to the demand for wind power projects. In the five years leading up to 2013, the United States installed more than 43 GW of wind, leading to a cumulative installed capacity of more than 61 GW by the end of 2013 [9]. With the rapid increase in turbine installations, more original



Sources: Wiser and Bolinger [6], Bloomberg New Energy Finance; American Wind Energy Association

Figure 2-36. Domestic wind turbine nacelle assembly, blade, and tower manufacturing capacity vs. U.S. wind turbine installations

equipment manufacturers established regional offices, developed local supply chains, and expanded U.S.-based manufacturing and assembly capacity [25]. Figure 2-36 shows how domestic nacelle assembly and blade and tower manufacturing capability compare with both growth in wind installations and projections for future growth.

In addition to expanded nacelle assembly manufacturing capability, by the end of 2013, the U.S. domestic supply chain had the capacity to produce 10,000 blades (6.2 GW) and 4,300 towers (8 GW) annually [9]. This trend demonstrates the ability of the industry to invest in new domestic manufacturing capacity, which, in turn, can facilitate rapid increases in demand needed to support the deployments in the *Wind Vision Study Scenario*.

Due to the lack of near-term (~two years) demand—driven primarily by uncertainty about the extension of the PTC— only 1 GW of additional wind was installed in 2013. This represents a 92% drop in the market relative to 2012 [9]. Most, if not all, original equipment manufacturers and their suppliers scaled back capacity. In addition to the closure of five major wind-related manufacturing facilities and the exit of seven additional facilities during 2012, two major wind-related manufacturing facilities were shuttered during 2013 [7]. Further information on the domestic supply chain capacity can be found in Appendix E.

Domestic Content and International Trade

The wind industry supply chain has become increasingly globalized, with manufacturing locations based upon factors including national policies, labor costs, transportation costs, original equipment manufacturer supply chain strategies, and technology development. Component country of origin varies widely, depending upon the type of components. For example, larger components that are more costly to transport (i.e., blades and towers) are more likely to be manufactured in the domestic market.

Within the U.S. market, the overall share of domestically manufactured turbines and components has increased over the last decade, leading to a decrease in the share of imported wind turbines and select components despite record installations and industry growth. The combined import share of *selected* wind equipment tracked by trade codes (e.g., blades, towers, generators, gearboxes and complete nacelles), when presented as a fraction of total equipment-related turbine costs, declined from roughly 80% in 2006 and 2007 to 30% in 2012 and 2013 [6]. Domestic content for some large components, such as blades and towers, ranged between 50% and 80% in 2012–2013. The share of wind turbine project costs (including project costs for non-turbine equipment sourced domestically), was approximately 60% in 2012. Domestic content was considerably below these levels for generators and much of the other equipment internal to the nacelle, however, and much of this equipment is not tracked by trade codes [6].

National policies have also affected the global supply chain, which directly influences the percentage of imported vs. domestic content of some components. U.S. exports of wind-powered generating sets increased from $16 million in 2007 to $421 million in 2013, not including export of components that would add to the total export value (e.g., blades and towers) [6]. The two largest markets for U.S. exports between 2006 and 2013 were Canada (52%) and Brazil (33%) [6]. Policies that continue to drive local content requirements in Brazil, and until December 2013 in Canada as well, may limit U.S. exports to those markets. On the import side, China provided more than 50% of total imported towers to the United States in 2011 and 2012. In 2012, however, a trade dispute over low prices led the U.S. Commerce Department to levy large tariffs on imported towers from China. This could result in supply shifts, resulting in some additional domestic capacity and imports from countries not impacted by the tariffs [25]. Further details on the value of imports and exports can be found in Appendix E.

Raw Materials

One of the considerations in the *20% Wind Energy by 2030* report was the availability of raw materials to meet that scenario. Wind turbines are primarily constructed of abundantly available materials such as steel, glass, copper, and aluminum, so supply concerns are generally minimal. A supply chain analysis of wind technology commissioned by the International Energy Agency (IEA), however, identified two potential bottlenecks for highly critical materials: carbon fiber used in advanced rotor blades, and rare earth metals used for some permanent magnet generators [130]. While there have not been any fundamental raw material supply concerns for wind turbines, the trends in commodity material prices in the decade leading up to 2013 have had a significant impact on wind turbine prices and design choices. Analysis performed by LBNL estimated that commodity price changes accounted for nearly 12% of the overall general turbine price *increase* that occurred in the industry between 2002 and 2008, and nearly 35% of the price *decrease* from 2008 to 2010 [131]. More information on raw material trends can be found in Appendix E.

Repair and Remanufacturing

The market for repair, replacement, and repowering wind plants will continue to grow as installed assets of more than 61 GW of cumulative installed wind capacity age. While 52% of the installed U.S. wind turbine fleet was less than five years old in 2014, 34% of installed wind turbines were commissioned between 1982 and 2001 [132]. With O&M representing around 25% of lifetime turbine costs and levelized replacement costs representing 30% of O&M [28], there is a growing aftermarket for remanufactured and replacement components to support expansion for domestic manufacturers. Further details on repair and remanufacturing can be found in Appendix E.

2.6.2 Transportation and Design Impacts

The U.S. market has expanded to include lower wind speed sites (average wind speeds <7.5 m/s) closer to population centers. This is in part because of technological advancements and policy drivers. In some regions, it is also due to limited access to available transmission lines. As a result, from 1998 to 2013,

Turbines with larger blade and tower components can capture more wind at lower wind speed sites, but pose transportation and logistics challenges.

the average estimated quality of the wind resource at 80 m for newly installed wind projects dropped by approximately 10% [6]. This trend has increased the complexity and cost of transportation logistics because components such as blades and towers have increased in size to capture the resource at lower wind sites. As a result, existing transportation infrastructure is increasingly impacting component designs to balance energy production with transportability.

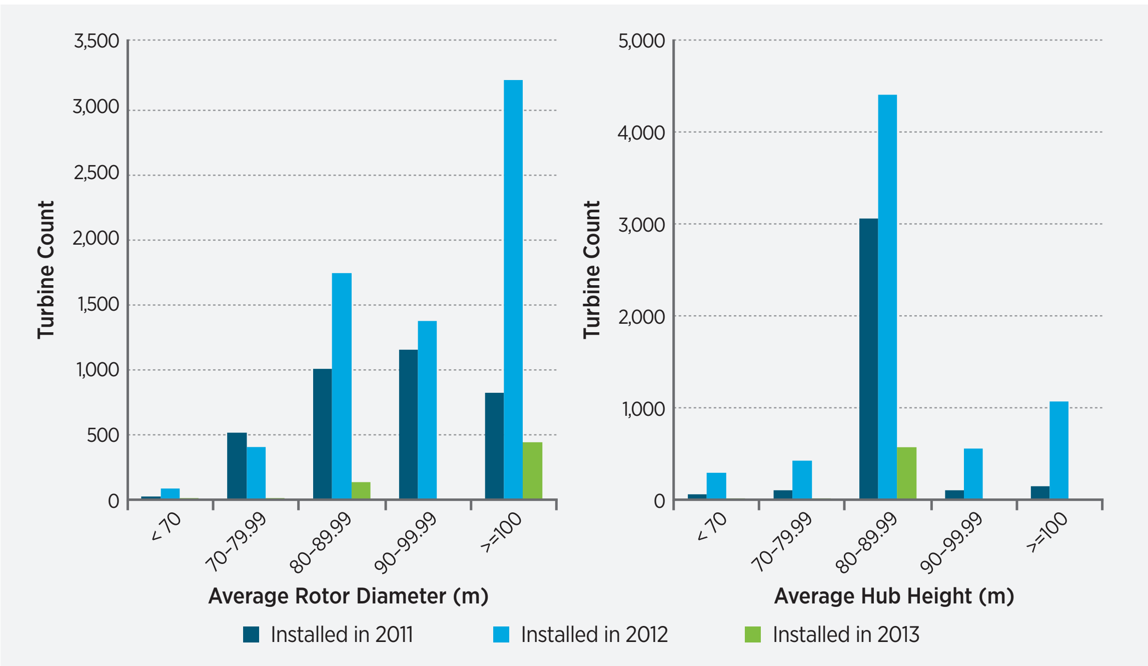
Transportation Logistics

Installed turbine power ratings have continued to rise, to an average of 1.95 MW in 2012 including multiple models at more than 2 MWs and above [53]. As OEMs seek to capture more wind at lower wind speed sites, average rotor diameters have increased rapidly. Tower components have also increased in size and weight to access better winds higher above the ground (Figure 2-37). Wind turbine blades longer than 53 m begin to present a transportation obstacle due to the large turning radius, which hinders right of way or encroachment areas within corners or curves on roads or railways (Figure 2-38). Tower sections are generally limited to 4.3 m in diameter, or 4.6 m where routes permit, to fit under overhead obstructions.

In addition to the physical limitations associated with wind components, each state along a transportation route has different requirements to obtain permits. This problem is exacerbated by higher volumes of shipments as wind turbine deployments increase. States are shifting the burden of proof for the safety of large, high-volume shipments to the wind industry. To address the increased complexity and resulting costs and delays associated with these logistics challenges, AWEA's Transportation and Logistics Working Group is coordinating with the American Association of State Highway and Transportation Officials to harmonize permitting processes across states. The increased size, mass, and quantity of wind components has resulted in more actively managed wind turbine transportation logistics, making use of a variety of land transportation methods and modes. This has resulted in increased project costs of up to 10% of capital costs for some projects [133]. Further details about trends in transportation logistics for wind projects can be found in Appendix E.

Design Impacts

Transportation constraints increasingly impact the design of wind turbine components, leading to higher capital costs resulting from suboptimal design. A prime example can be found in the industry-standard rolled steel wind turbine towers, which are limited to a structurally sub-optimal 4.3 m diameter to comply with size and weight limits of U.S. roads. While it is possible to construct towers with hub heights up to 160 m at this constrained diameter, this height results



Note: In 2013, only 1 GW of wind capacity was installed, largely driven by the PTC expiration in 2012.
Source: AWEA 2014 [9]

Figure 2-37. Rotor diameter and hub height trends of wind turbines, 2011–2013

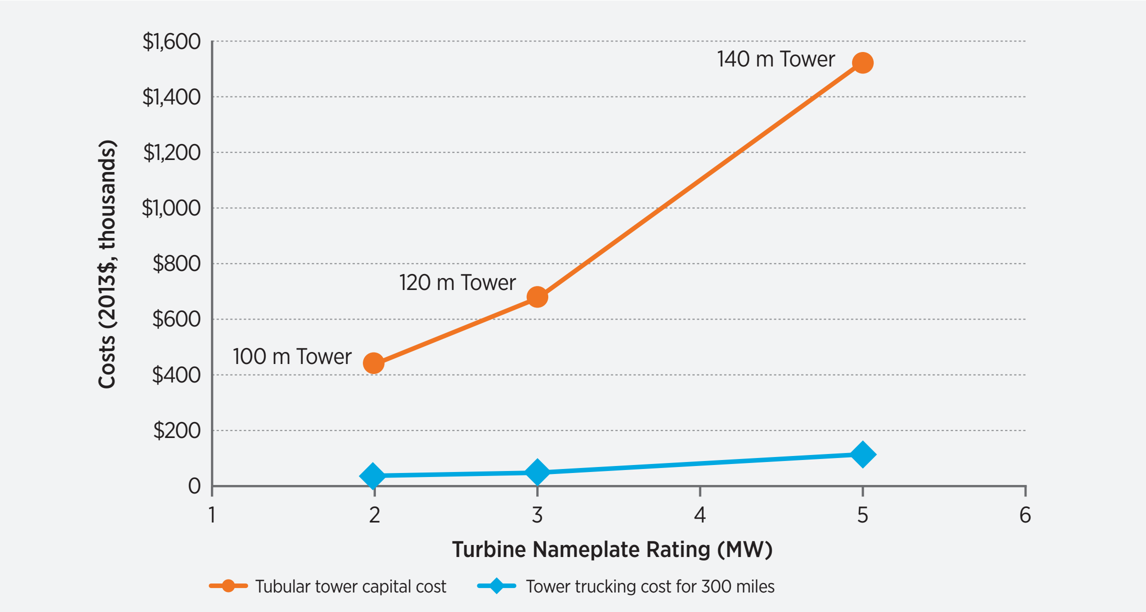
Source: SSP Technology

Figure 2-38. Example of wind turbine blades transportation obstacles

in an exponential increase in the mass and cost of rolled steel towers as plotted in Figure 2-39. Under transportation constraints as of 2014, tall towers are not economical in the sizes necessary to deploy wind in new, low and moderate wind speed land areas that are of interest to the industry to support cost reductions described in Section 2.1.3. It is important to note that these capital costs are substantially larger than the cost to transport the tower sections. Similar transportation-design tradeoffs impact blades with respect to other aspects such as maximum chord dimensions. Details about some proposed solutions for on-site manufacturing of towers to mitigate transportation constraints can be found in Appendix E.

2.6.3 Installation

Because of the lift height and mass, hoisting a wind turbine nacelle onto its tower requires the largest crane capacity of all wind turbine construction and installation phases. The masses of a 3-MW nacelle assembly and a 5-MW nacelle assembly are approximately 78 metric tonnes (t) and 130 t, respectively, without the gearbox and generator (104 t and 173 t with those components installed). Continued increases in tower heights and machine ratings are driving higher nacelle and blade weights. As a result, the availability, scheduling, and logistics of larger cranes have become increasingly challenging. Alleviating this challenge could influence future wind deployment by facilitating cost-effective development in more regions



Source: Cotrell [134]

Figure 2-39. Estimates of trucking and capital costs for conventional tubular towers, 2013

of the United States. Analysis performed by NREL indicates that having installation equipment capable of hoisting a 2.4-MW turbine onto a 140-m tower would increase the economically deployable area for wind by 614,000 km^2 (237,000 mi^2), especially in the southeastern United States [134]. Further details can be found in Appendix E, Section E.6.

Because mobile cranes capable of installing the majority of turbines deployed in the United States are of a common size used for construction and other industries, an ample supply of such cranes existed into 2014. As the number of turbines installed at 100 m hub heights and above has increased, however, concerns about the availability of larger capacity cranes has grown. Table 2-6 shows the sharp drop in available U.S. cranes when shifting from the standard 600-ton to the 1,250–1,600-ton class cranes needed for taller towers and heavier nacelles.

Another challenge with larger crane classes is difficulty transporting them to and maneuvering them within the wind plant, especially in complex terrain. A 1,600-ton crane has a width of nearly 13 m (41 feet), wider than a two-lane interstate highway (including shoulders), and requires more than 100 semi-tractor trailers to transport it between projects. This makes transportation between turbines difficult and costly. Further details on construction equipment trends can be found in Appendix E.

Table 2-6. Crawler Crane Availability in 2013 Relative to Wind Turbine Hub Heights

Crawler Crane Class	Approximate Number of Cranes in United States	Applicable Turbine Sizes
600 metric tonnes	85	3 MW/140 meter hub height
1,250–1,600 metric tonnes	10	5 MW/150 meter hub height 3 MW/160 meter hub height

Source: Cotrell [134]

2.6.4 Conclusions

Based on installation experience from 2006 to 2013, expanded domestic manufacturing to reach deployment levels of the *Wind Vision Study Scenario* for 2020 and 2030 will not be constrained by raw materials availability or manufacturing capacity. With recent domestic demand stability, wind manufacturing has moved toward higher domestic content. Past experience indicates unstable demand may drive reductions in domestic content and potentially shift equipment production overseas. Dips in demand have directed resources to other industries and could slow the return to high levels of deployment. Continued innovation in turbine design, manufacturing, transportation, and construction will be needed to overcome logistical barriers, reduce wind turbine cost, and improve international competitiveness. To capture more wind at lower wind speed sites, turbines with larger blade and tower components pose additional challenges for transportation logistics.

Section 4.3 discusses several *Wind Vision* roadmap actions regarding supply chain, manufacturing, and logistics including: increasing domestic manufacturing competitiveness with investments in advanced manufacturing and research into innovative materials; developing transportation, construction and installation solutions for deployment of next-generation, larger wind turbines; and establishing domestic offshore manufacturing, supply chain and port infrastructure.

2.7 Wind Integration and Delivery

Wind power has become a major source of electricity supply in the United States and around the world. Experience with the transmission, integration, and delivery of this electricity has verified the conclusions of numerous integration studies: No technical limits or obstacles have been identified that would prevent wind-generated electricity from meeting even greater portions of electricity demand in the United States. There may be a need for institutional or operational practice to change in some areas, however, so that wind power can be integrated successfully at increasing penetrations.[52]

Wind turbine technology has evolved to incorporate more grid-friendly features. System balancing could be a concern at higher penetrations. Reforms in many market areas with robust energy markets (e.g., PJM Interconnection, Midcontinent Independent System Operator [MISO]), along with market evolution in areas such as the Southwest Power Pool and the emerging Energy Imbalance Market, have improved the tools available to the system operator to manage the increased variability and uncertainty of wind power. Some areas now incorporate wind power into the economic dispatch process.[53]

The electric power network operates reliably with high wind contributions (10% and higher) today, with minimal impacts on network operating costs.

In regions with wind power contributions up to 20% of annual electrical demand in 2013, electric power systems operated reliably without added storage and with little or no increase in generation reserves [7]. Wind has also been proven to increase system reliability during some severe weather events. For example, in February 2011, cold weather disabled 152 power plants in Texas, mostly coal and natural gas. Wind generation produced approximately 3,500 MW of output during this event, helping to avoid outages [135]. Experience with wind generation confirms that opportunities exist to increase grid operating efficiency and reduce costs by increasing flexibility.[54]

Wind power has characteristics that differ from generation powered by nuclear, gas, and coal.[55] Because wind generation is driven by meteorological processes, it is intrinsically variable, from real-time, minute-to-minute fluctuations to yearly variations affecting long-term planning for utility operations.

52. The Intergovernmental Panel on Climate Change report on wind energy [85] provides a heavily referenced section summarizing the potential integration challenges of large amounts of wind.

53. See for example MISO 2013 Annual Market Assessment Report, available at *https://www.misoenergy.org/Pages/Home.aspx#*.

54. Flexibility is the ability of the power system to respond to variations in supply and/or demand.

55.. Solar energy has similar characteristics to wind power and can complement wind power with respect to the diurnal pattern of generation.

These characteristics can require changes in system operational practices and the potential addition of flexibility reserves to help manage increased variability and uncertainty from wind power.[56] Grid operators that have adapted operating practices, such as ERCOT and MISO, have seen integration costs and impacts that are less than predicted by many studies. Both ERCOT and MISO incorporate wind power plants into the economic dispatch, which results in more cost-effective operation of the power system. ERCOT provides an example of very low integration costs—approximately $0.50/MWh of delivered wind power. The only source of increased cost ERCOT could identify was a small increase in operating reserve requirements [136].

In the United States, studies to analyze the impact of wind power on planning and operation of power systems were performed *before* significant levels of wind were installed. As wind turbines and wind power plants were developed, the findings of the initial wind integration studies were confirmed: Large amounts of wind power can be reliably integrated, and even larger amounts can be integrated with cost-effective changes to grid operating procedures and added transmission capacity. The following discusses the studies as well as actual operating practice, which demonstrates how study results were confirmed by actual experience.[57]

In addition to studies described in this section that simulate operational characteristics of large amounts of wind power, significant levels of wind have also had an impact on the desired characteristics of other resources (generation, demand response, or storage) needed to complement wind power. For example, wind power provides limited contribution to planning reserves, often called "capacity value" [137]. As the wind penetration rate increases, at some point there will likely be a decline in per-unit capacity value of wind generation. This decline will depend on the geographic dispersion and statistical correlation of wind plant output levels across large regions, and will likely be moderate at correspondingly low-to-moderate penetration rates. The effect on overall electricity cost will depend on a number of items, including future carbon values, conventional fuel costs, and the cost of new flexible technologies that may include some combination of fast-response thermal or hydropower generation, along with demand response and electricity storage.

Section 2.7.1 summarizes some recently completed studies on wind integration, while Section 2.7.2 summarizes operational experience and highlights how large amounts of wind power can be reliably integrated into the power system. Flexibility, which is important for easily integrating wind into the power system, is discussed in Section 2.7.3. Transmission system capacity issues are addressed in Section 2.7.4. Section 2.7.5 discusses how industry organizations are addressing wind integration into the power system.

2.7.1 Wind Integration Studies

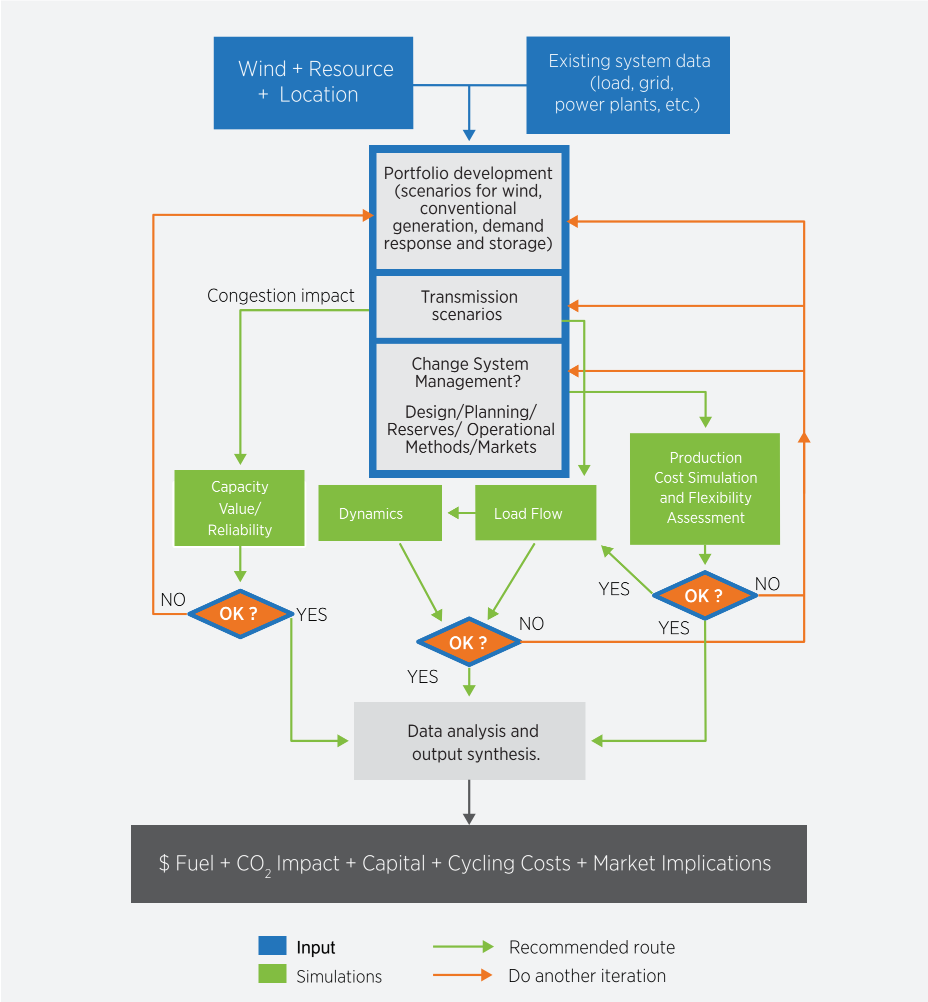
Large amounts of wind power have already been reliably integrated into the power system [25]. Numerous in-depth wind integration studies have confirmed that amounts of wind power far larger than the 2013 national average of 4.5% of end-use demand can be added to the power system without harming its reliability [138, 139]. Wind integration does not come without costs and impacts, however, including power system balancing and scheduling flexibility. It should be noted, though, that the addition of any type of generation will likely impose an integration cost and impact.[58] Many studies conducted in Europe and the United States indicate that wind power contributions up to and above 20% are technically possible, but with rising integration costs. These cost calculations are complex and specific to system and region [140]. A range of studies have quantified these balancing costs as roughly $1.40 to $5.60/MWh of wind power generated, generally increasing with wind power penetration, whereas the cost of wind power typically ranges from $30-60/MWh [141].

In order to understand the impacts of wind, utilities and transmission system operators have conducted integration studies of electric power system operation and planning that include low (a few percent) to high

56. Reserve generating capacity is equipment that is ready to add power to the grid to compensate for increased load or reduced generation from other units.

57. For more detailed discussion about wind power integration, see : *Review and Status of Wind Integration and Transmission in the United States: Key Issues and Lessons Learned* NREL TP-5D00-61911 [140].

58. See, for example, Milligan, M.; Ela, E.; Hodge, B.; Kirby, B.; Lew, D.; Clark, C.; DeCesaro, J.; Lynn, K. (2011). Integration of Variable Generation, Cost-Causation, and Integration Costs. Electricity Journal. Vol. 24(9), November; pp. 51-63. Available at *http://dx.doi.org/10.1016/j.tej.2011.10.011*



Source: IEA Wind [142]

Figure 2-40. Flowchart of a full wind integration study

(in excess of 20% of annual electricity consumption[59]) contributions of electricity from wind power. The basic methodology for carrying out a wind integration study has advanced significantly since the early 2000s. Originally, evaluations of wind power's impact on operations treated the technology as an incremental addition to an otherwise unchanged conventional power system. Studies prior to 2008 attempted to estimate the hypothetical cost of operating a power system with wind power compared to some other power source that is perfectly predictable and controllable. Most of those early studies estimated the resulting costs at up to $5/MWh of wind power [25].[60]

By 2013, integration studies had progressed to consider wind power as a fully integrated part of the generation fleet. Integration studies include the recognition that all generation sources have integration costs and that individual loads also have variability and uncertainty. More recent studies (after about

59. Wind power that provides an annual 20% share of consumption will, at times, have high instantaneous shares of electricity. See, for example, Lew et al., Western Wind and Solar Integration Study Phase 2. *http://www.nrel.gov*

60. A few studies found cost impacts up to $12/MWh. These studies examined relatively small balancing areas with limited electricity transfer capability to and from neighboring regions, and, in some cases, did not accurately represent the impact on power system operations. As discussed later in the section, these characteristics pose challenges for wind integration.

2010) capture not only the impacts of wind on system operation, but also the overall cost and emissions savings due to displaced thermal generation. Integration studies have evolved toward a comprehensive process that compares reliability impacts and overall system operating costs for alternative configurations of generators to serve system load [142]. This process is summarized in Figure 2-40. Although this figure is designed to show how integration studies should be performed, it also illustrates the relationship between various integration aspects that need to be evaluated when increasing levels of wind power are introduced into the power system. Although actual assessments of installed wind power impacts may not be performed in a systematic way, all of the elements below need to be successfully managed if wind power is to be effectively integrated into the power system.

Integration studies are important tools to help quantify the value of alternative approaches to adding increased amounts of wind to conventional generation and load management. Many wind integration experts now recognize that it is difficult—if not impossible— to separate wind integration costs from other impacts on the power system, e.g., displacing other generation. As a result, the focus of wind integration studies has shifted to broader evaluations of power system economics.

2.7.2 Operational Experience

Wind generation contributed 4.5% of U.S. net electric power sector demand in 2013 [82]. In that year, wind power in South Dakota and Iowa generated an amount equal to more than 20% of each state's overall electric energy consumption. In Colorado, instantaneous contributions from wind up to 60% were successfully managed by the power system operator [9]. Figure 2-41 shows recent high-wind penetration events in the United States. In all of these examples, the electric power system continued to operate reliably.

Other countries are using even higher shares of wind power to meet electricity needs. Denmark leads in wind generation, obtaining 32.7% of its electricity from wind in 2013, followed by Portugal (23.5%), Spain (20.9%), Ireland (16.3%), and Germany (8.9%) [143]. Instantaneous contributions of 93% were recorded in Portugal and 50% in Ireland in 2012 [142]. This experience by grid operators facilitates better understanding of the impacts of wind on the power system, as well as opportunities to take advantage of wind power's benefits and minimize its costs.

Operational experience has confirmed the findings of wind integration studies: large amounts of wind power can be reliably integrated into the power system. Experience also supports the conclusion that efficient grid operating procedures such as large or coordinated balancing areas,[61] fast-interval generation scheduling and dispatch,[62] setting wind generator schedules as close as possible to the dispatch time to minimize forecast errors, and the use of wind power forecasting can greatly facilitate wind integration and reduce costs.

Most North American power markets now integrate wind power into their security-constrained unit commitment[63] and security-constrained economic dispatch[64] process, allowing the dispatch of wind plants along with conventional power plants based on current grid conditions and economics. This effectively gets wind into the real-time economic optimization process for running the power system, and in turn, encourages the participation of wind plants in the day-ahead markets. Security-constrained economic dispatch also makes wind dispatchable and economical, allowing some degree of wind-plant output control by the system operator.[65] This allows wind forecasts to become more useful and valuable to wind plant operators, market participants, and system operators, because wind is better integrated into systems and markets.

61. A balancing area is a predefined area within an interconnected transmission grid where a utility, an independent system operator, or a transmission system operator must balance load (electrical demand) and electrical generation while maintaining system reliability and continuing interchanges with adjoining balancing areas. An interconnected grid can have one or many balancing areas. For example, the Western Interconnection, which covers much of the western U.S. and western Canada, has 35 balancing areas, while the Texas Interconnection has only one.

62. Dispatch is the real-time centralized control of the on-line generation fleet to reliably and economically serve net system load.

63. Unit commitment is the process of starting and synchronizing power plants to the grid to minimize operating cost and maintain power system reliability.

64. Economic dispatch is the process of altering the output of one or more generators on an economic basis.

65. Wind plant output can be ramped down easily; ramping up is possible only if the plant is operating below the maximum level allowed by current wind conditions.

In 2013, grid operators with extensive experience using wind on their systems concluded the need for additional operating reserves associated with wind are low.[66] ERCOT calculated that the incremental reserve needs for about 10 GW of wind on its system translated into a dollar value addition of $0.50/MWh of wind, or about 6¢/month on a typical Texas household's $140 monthly electric bill.[67] Similarly, MISO, which serves the U.S. Midwest and Manitoba, Canada, has described more than 12 GW of wind generation as having little to no effect on its reserve needs [144].

Energy markets react to and compensate for variability and uncertainty in the aggregate wind and load. ERCOT and MISO, both with approximately 9% of annual generation coming from wind power, have been able to integrate large amounts of wind with minimal increases in reserve needs because they employ day-ahead, hour-ahead, and 5-minute energy markets. These system operators also incorporate wind power into power system dispatch [145] by setting the output schedule for wind energy based on the wind output level 10 minutes before real-time, reducing the frequency and magnitude of forecasting error.

Other initiatives have resulted in intra-hour scheduling or dispatch. For example, the Federal Energy Regulatory Commission's (FERC's) Order 764 (Integration of Variable Energy Resources) required public utility transmission providers to allow transmission customers to schedule at 15-minute intervals. Bonneville Power Administration implemented a successful intra-hour scheduling pilot in 2011 that is now a formal business practice.

Unlike ERCOT and MISO, operators in much of the western United States use hourly energy schedules and set the wind power output based on wind output an hour or more before real-time. During these longer intervals, wind power output can change significantly. Shorter (5-minute) scheduling and dispatch would significantly improve the ability of the power system to effectively integrate large amounts of wind power, whereas the current hourly scheduling practice increases reserve requirements. In late 2014, an Energy Imbalance Market began operating within the California Independent System Operator and PacifiCorp operating regions, using a security-constrained economic dispatch at 5-minute time steps. NV Energy will likely join this market in 2015, and the Northwest Power Pool is undertaking the analysis of a similar security-constrained economic dispatch for the Northwest.

More accurate wind forecasting has helped to reduce system operating challenges from unexpected wind plant outputs in all time frames. Forecasts are particularly important in the day-ahead, hours-ahead, and minutes-ahead time frames for scheduling wind generation into power systems and markets. Developments in wind power forecasting have also reduced the integration challenges associated with variable generation technologies [146, 147, 148]. By 2014, most parties were comfortable with making the system operator's forecasts publicly available in some form, and then combining those results with additional forecasts and information from market participants.

Grid-friendly features that have evolved include low-voltage ride-through, which allows wind turbines to stay online during low-voltage events, thus contributing to system stability. In addition, frequency response—the ability of the wind turbine to increase or decrease generation to help support nominal system frequency of 60 Hertz—is a feature of modern wind turbines. The ability to respond to automatic generator control signals allows wind turbines to provide regulation service, which is system balancing on very short time scales—from about 4 seconds to several minutes, depending on the region. Finally, simulated inertial response provides fast response during a disturbance. With the potential retirement of large coal generators during the next several years, system inertia will decline. This is attracting significant attention in the power system community, which

66. Operating reserves are generating equipment that is ready to add power to the grid and demand response that is ready to reduce consumption to compensate for increased load or reduced generation from other units (such as wind, or solar, and conventional power plants).

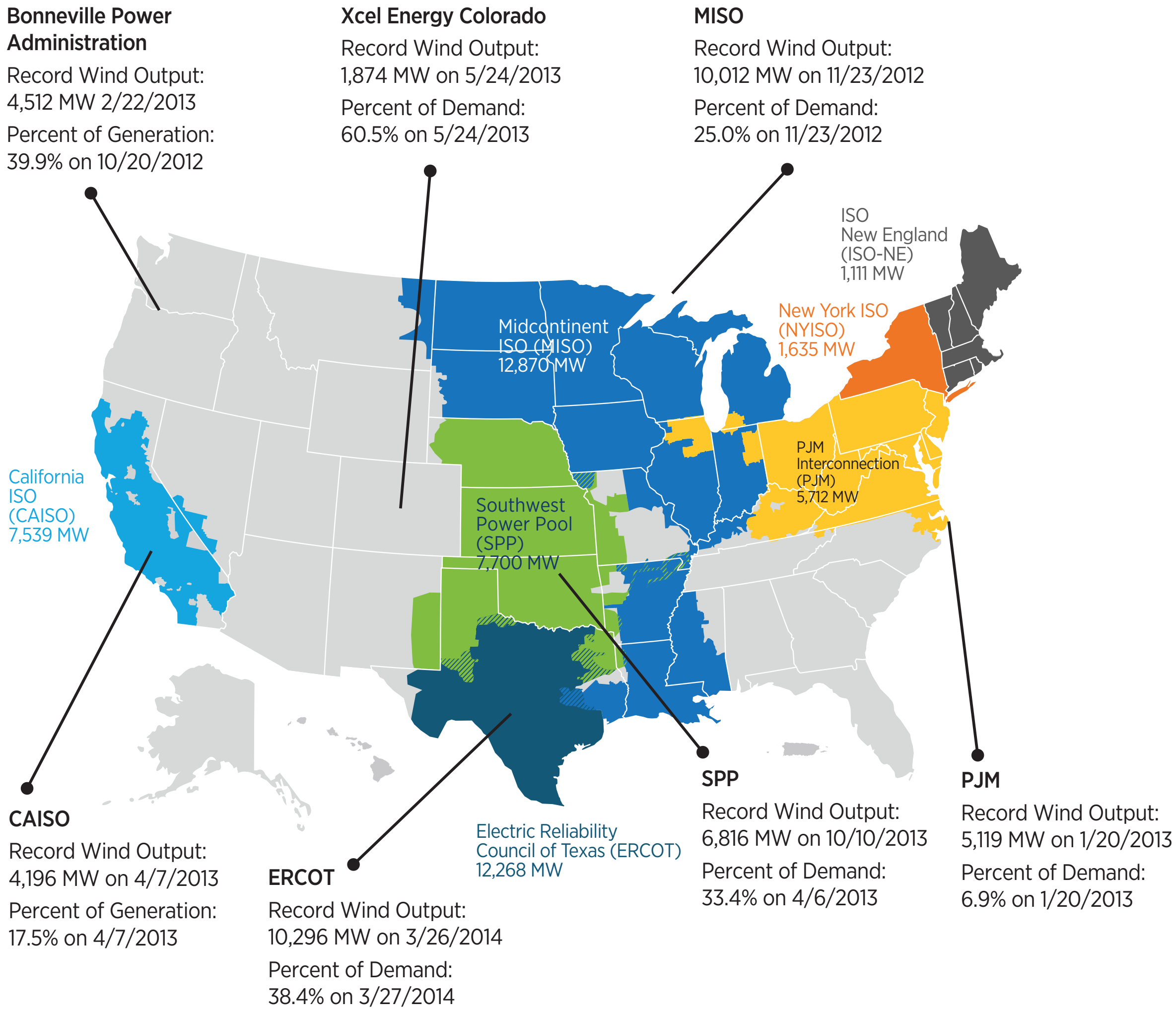
67. Based on a calculated wind integration cost of $0.50 per MWh of wind power, which equals $.046 per MWh of total load served in ERCOT at 9.2% wind power use (*http://uvig.org/events/#!/5701/2013-forecasting-workshop-2*), multiplied by the 1.262 MWh used per month by the average Texas household (Table 5a at *http://www.eia.gov/electricity/sales_revenue_price/*).

to date has not performed rigorous analysis of how simulated inertial response from wind turbines in the face of significant coal retirements will impact system stability. Such studies will likely gain momentum.[68]

Over the past few years, wind plants have been instrumental in maintaining reliable system operation during market changes and weather events. Text Box 2-7 describes wind's contributions during some of these events.

2.7.3 Flexibility

Flexibility is important for easily integrating wind and can come from changes to grid operating practices, changes in market design, or physical changes to power system resources. Power systems operating successfully with large wind contributions have adequate levels of flexibility that facilitate variable generation. Flexible power systems have some or all of the following characteristics:



Note: Acronyms used in graphic: Midcontinent ISO (MISO); PJM Interconnection (PJM); Southwest Power Pool (SPP); Electric Reliability Council of Texas (ERCOT); California ISO (CAISO); Independent system operator (ISO) .

Source: AWEA [7]

Figure 2-41. Key grid operating areas experiencing high instantaneous contributions from wind, 2012–2013

68. See NREL Western Wind and Solar Integration Study *http://www.nrel.gov/electricity/transmission/western_wind.html and* Active Power Control project *http://www.nrel.gov/electricity/transmission/active_power.html*) for more information.

Text Box 2-7.

Utility Wind Management

- While wind power output changes with the wind speed, such changes occur far more slowly than the unexpected outages that can occur at large conventional power plants.
- Wind power output is predictable using weather forecasting, and the technology can often be used to fill demand when conventional power plants fail.
- Long-term PPAs for wind power provide a buffer against price increases for other fuels.
- In Nebraska, as natural gas prices surged because of demand in the winter of 2013, 300 MW of wind provided 13% of demand and kept prices down. The utility shut down natural gas generation because prices were up more than 300%.
- Across New England, high output from the region's wind plants moderated the effect of high natural gas prices in 2013.

- Frequent and short dispatch and scheduling intervals with a look-ahead function to allow full access to physical flexibility of the resource (generation, demand response, and storage);
- Operating responsibilities shared over large geographic areas to allow access to a large fleet of power plants for energy generation and reserves;
- Connectivity[69] through the electrical transmission infrastructure that allows regional sharing, provides access to distant available generation of all types including wind, and allows averaging of non-coincident wind generation outputs from different locations;
- Demand-side management to help maintain the balance between generation and demand;
- Generators or cost-effective energy storage designed for rapid ramping of output levels, wide operating ranges, and short start-up times; and
- Appropriate operating procedures to access elements of flexibility.

Figure 2-42 illustrates many of the system flexibility elements discussed in this section and indicates the degree to which various types of power systems exhibit these elements. The most flexible institutional framework today appears to be a large regional transmission organization with spot markets and sub-hourly markets (represented in the figure with a green box with 10). Such a framework would encourage flexibility attributes needed for power system operation. The least flexible institutional framework is a small, vertically integrated local utility with a small balancing area and no sub-hourly markets or systematic sub-hourly economic dispatch.

ERCOT, MISO, and other operators with large amounts of wind power have grid operating responsibilities over large geographic areas (Figure 2-42). Aggregate wind power variability is reduced by averaging over large areas when weather patterns move across an area that has many wind projects. Large balancing areas also include more diverse generators and sources of demand response. Centralized energy markets with fast generator dispatch and robust ancillary services[70] markets make these power systems more flexible.

State-of-the-art wind plants with advanced controls can actually provide increased flexibility to the system. These plants can help the grid by providing grid services such as reactive power even when wind is not blowing [150], synthetic inertia, governor response, and regulation service, if proper incentives are provided.[71] The ability for wind generation to be dispatched below maximum power wind conditions

69. Connectivity is the ability to transfer electrical energy from one location to another through transmission lines and related infrastructure.

70. Ancillary services refer to the ability to respond quickly to changing system conditions, at any season or hour, when human operators or computers give the order. This process ensures demand-generation balance, system reliability and stability, and voltage support.

71. Synthetic inertia, governor response, and regulation refer to control of wind generator output in time frames ranging from cycles to seconds to emulate the response provided by conventional generators.

Accommodating Wind Integration

Large balancing area	Geographically dispersed wind and solar	Wind forecasting effectively integrated into system operations	Sub-hourly energy markets	Fast access to neighboring markets	Non-spinning and 30-minute reserves for wind event response	Regional transmission planning for economics and reliability	Robust electrical grid	More flexible transmission service	Flexibility in generation	Responsive load	Overall	Example Utility Structures
10	8	7	10	7	2	7	6	7	7	3	7	Large regional transmission organization with spot markets
6	6	6	3	3	2	6	4	7	2	2	4	Smaller independent system operator
1	3	2	1	2	1	2	3	2	2	2	2	Interior west and upper Midwest (non-MISO)
7	6	6	2	2	2	5	4	2	5	2	4	Large vertically-integrated utility
1	3	2	1	2	1	2	4	2	2	2	2	Smaller vertically-integrated local utility
									8			Unconstrained hydro system
									3			Heavily fish-constrained hydro system

Note: System flexibility increases as the color of the numbered boxes progresses from red to green, and as the number increases from 1 to 10. The items at the top of the table are those attributes that help efficiently integrate wind power into power systems operation. Although the table uses a simplistic 1–10 scoring system, it has proven useful as a high-level, qualitative tool. The red, yellow, and green result cells show the ease (green) or difficulty (red) that a hypothetical system would likely have integrating large amounts of wind power. RTO is regional transmission organization; ISO is independent system operator.

Source: Milligan [149]

Figure 2-42. Characteristics that help facilitate wind power integration

means wind power can provide fast and accurate response, which can be economically attractive when other options are limited. As with other ancillary services and providers, the necessary incentives must be in place to encourage this flexibility. NREL is conducting research on wind turbine active power controls along with market incentives necessary to induce the provision of these services when they are cost effective.[72]

2.7.4 Transmission System Capacity

Transmission is essential for bringing new wind capacity online and accessing the highest-quality, lowest-cost wind resources. Depending on its location and other factors, a land-based wind plant may require new transmission lines or increased capacity on existing lines. Grid-connected distributed wind

72. See NREL's *Active Power Controls* Web page at *www.nrel.gov/electricity/transmission/active_power.html*

projects might not require new transmission or distribution lines because distributed wind systems can effectively use available capacity on existing local distribution grids or are connected directly to an existing electrical service for a home, farm, or other facility.

Many sites with the nation's best wind power resources have minimal or no access to electrical transmission facilities.

Some of the nation's best wind resource regions are not accessible because transmission to these often rural regions may not exist.[73] Designing and building transmission does not present technical difficulties; however, siting the new lines and allocating the cost are both contentious topics (with or without wind) and there is currently a limited framework to resolve these issues. Broad allocation of transmission cost and proactive planning for transmission and siting are important to stimulate investment in new transmission capacity.

Wind power deployment has focused on the Great Plains region due to high average wind speeds and vast tracts of open land. Due to a lack of transmission and the long distance to load centers, however, the U.S. Interior continues to have substantial untapped resources. In 2013, a lack of transmission was listed as the primary siting-related constraint to expanded deployment [151]. In some regions, such as the Columbia Gorge in the Pacific Northwest, a significant amount of wind power can be developed close to existing transmission. There may be times that the transmission system is congested, resulting in the

Text Box 2-8.

Competitive Renewable Energy Zones in Texas

In the mid-2000s, wind generation in parts of Texas was being regularly curtailed when generation exceeded the capacity of the transmission lines. At the same time, wind development was being encouraged by the state's RPS, but developers were finding that many of the best areas for wind generation had little or no available transmission capacity. Installation of wind turbines continued, but in lower wind speed areas. Developers focused on available transmission capacity as the primary consideration.

In 2005, the Texas Legislature passed a law that required the Public Utility Commission of Texas to designate one or more Competitive Renewable Energy Zones (CREZ) and to approve transmission improvements to connect these zones with load centers in the ERCOT region. This solved the chicken-and-egg issue by determining that the transmission should come in advance of the wind (or solar) development for the good resource zones. Five zones and a CREZ transmission plan were approved in 2008.

The completed circuits of the Texas transmission plan relieve constraints on existing wind generation. Before the CREZ plan, existing and planned wind generation of 6,900 MW was located in the region and curtailment reached 17% of potential wind generation in 2009 (Table 2-7). By 2012, curtailment was down to 3.8%, falling to 1.2% in 2013, and, by 2014, 10,970 MW of wind generation was operating in ERCOT.

The new CREZ transmission has provided connection between wind resources in the Texas Panhandle (home to some of the best wind resources in the country) and the ERCOT market. As a result, wind developers have shown significant interest in the area. According to ERCOT, by early 2014, interconnection agreements had been signed for proposed projects totaling 6,947 MW, and applications for connection had been made for another 24,000 MW. The response was so overwhelming that the grid operator was already exploring additional Panhandle transmission expansions shortly after the CREZ was completed [7].

73. See, for example, American Transmission Company, *http://www.atcllc.com/learning-center/delivering-renewable-energy/*.

Table 2-7. Estimated Wind Curtailment by Area in GWh (and as a Percentage of Potential Wind Generation)

	2007	2008	2009	2010	2011	2012	2013
ERCOT	109 (1.2%)	1,417 (8.4%)	3,872 (17.1%)	2,067 (7.7%)	2,622 (8.5%)	1,175 (3.8%)	363 (1.2%)
Southwestern Public Service Company	N/A	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)	N/A	N/A
Public Service Company of Colorado	N/A	2 (0.1%)	19 (0.6%)	82 (2.2%)	64 (1.4%)	115[a] (2.0%)	112[a] (1.7%)
Northern States Power Company	N/A	25 (0.9%)	42 (1.7%)	44 (1.7%)	59 (1.6%)	125 (3.0%)	284 (5.9%)
MISO, less Northern States Power Company	N/A	N/A	250 (2.0%)	780 (4.2%)	792 (3.4%)	724 (2.5%)	1,470 (4.6%)
Bonneville Power Administration	N/A	N/A	N/A	5[b] (0.1%)	129[b] (1.4%)	71[b] (0.7%)	6[b] (0.1%)
New York Independent System Operator	N/A	N/A	N/A	N/A	N/A	9 (0.3%)	50 (1.4%)
PJM Interconnection	N/A	N/A	N/A	N/A	N/A	125[c] (2.0%)	284 (1.9%)

a. Xcel Energy declined to provide 2012 and 2013 curtailment data for its Southwest Public Service and Public Service Company of Colorado service territories; Public Service Company of Colorado 2012/2013 data are estimated from Bird et al. (2014) [153].

b. A portion of Bonneville Power Administration's curtailment is estimated assuming that each curtailment event lasts for half of the maximum possible hour for each event.

c. 2012 curtailment numbers for PJM are for June through December only (data for January through May 2012 are not available).

Source: Wiser and Bolinger [6]

curtailment (manual or other reduction in wind power output) of wind power.[74] In other places, a trade-off exists between investing in new transmission to reach better wind resource areas and developing less-windy locations near existing transmission.

Transmission line planning criteria often dictate that new transmission capacity will not be built in advance of need, and wind developers are not willing to start projects if they have to wait five years—or in some cases longer—for new transmission to be completed. This so-called "chicken-and-egg" problem has been addressed in Texas using a model that could apply in other areas (see Text Box 2-8).[75]

Meanwhile, progress has been achieved nationally on overcoming transmission barriers, and curtailment of wind plants has been reduced from its 2009 peak. Since 2008, the United States has installed more than 2,300 circuit miles of new transmission lines annually. An additional 18,700 total circuit miles are planned for 2014 through 2019. In 2012, AWEA identified 19 near-term transmission projects that—if all are completed—could carry almost 70 GW of wind power capacity [154]. MISO has undertaken "multi-valued" projects, proposing and constructing transmission network upgrades that provide lower-cost energy [155]. FERC Order 1000[76] was affirmed in August 2014. The Order requires public utility transmission

74. Curtailment may be part of market operations in an RTO/ISO setting, in which wind plants bid their minimum running price. In non-RTO areas, or RTO regions that have not implemented economic dispatch for wind power, the specific mechanism for curtailment varies.

75. More details regarding this plan are available in the report: CREZ Transmission Optimization Study, *http://www.ercot.com/search/results?q=CREZ+Transmission+Optimization+Study* [152].

76. See *www.ferc.gov/industries/electric/indus-act/trans-plan.asp* for details.

providers to improve intra- and inter-regional transmission planning processes and to determine cost-allocation methodologies for new transmission plants. States, grid operators, utilities, regional organizations, and DOE also continue to take proactive steps to encourage transmission investment. Despite this progress, siting, planning, and cost-allocation issues remain key barriers to transmission investment, and wind curtailment continues to be a problem in some areas, mainly as a result of constrained transmission.

2.7.5 Industry Organizations are Addressing Wind Integration

Engagement by the power system industry is necessary to achieve the reliable integration of large amounts of wind power. The following discussion of organizations addressing integration is not exhaustive, but is intended to illustrate some of the key institutional involvement that has had an effect on wind integration.

Utility Variable-Generation Integration Group

The Utility Variable-Generation Integration Group (UVIG), previously known as the Utility Wind Integration Group, was established in 1989 as a forum for the critical analysis of wind and solar technology for utility applications. UVIG is a member-based organization made up of investor-owned utilities, public power providers, electric cooperatives, independent system operators, and other non-utility firms engaged in the wind and solar business. The organization provides credible information on the status of wind and solar technology, deployment and power-system integration [156]. It also encourages utility-to-utility dialogue on many of the integration and operational challenges of adding variable generation to the power generation portfolio in locations worldwide. UVIG has more than 160 members from the United States, Canada, Europe, Asia, and New Zealand.

North American Electric Reliability Corporation

Anticipating substantial growth of variable generation, the North American Electric Reliability Corporation's (NERC's) Planning and Operating Committees created the Integration of Variable Generation Task Force (IVGTF).[77] The task force is executing a three-phase approach to assess potential reliability impacts of wind and solar generation on the electric power system, and to recommend actions for NERC to implement [137]. NERC utilized technical experts from throughout the electric power industry to develop broad-based consensus documents as work products from this effort. The IVGTF effort is an ongoing process that incorporates continued operating experience and reflects advances in equipment and analysis tools. Some of this work is being transitioned to the Essential Reliability Services Task Force (ERSTF). As this work moves forward, the various task forces will evaluate whether changes are needed to NERC reliability standards or recommended practices, and the outcome could have a large impact on how much wind power can be added to the power system.[78] Dynamic stability studies are needed to ensure reliable operation of high wind power penetrations—some of these are underway and will be completed by early 2015.

Federal Energy Regulatory Commission

FERC's purview is the regulation of interstate power and energy transfers and markets, and the reliability of the bulk power system. A number of FERC actions have spurred the development of bulk power markets, and resulted in the formation of independent system operators and regional transmission organizations in the United States. Many of these actions were not specific to wind or other variable renewable energy sources, but they provided the framework for fundamental changes in bulk power market structures that increase the economic efficiency of operation, with or without wind power. In December 2005, FERC issued Order 661-A, which specified rules for low-voltage ride-through for wind turbines. Other FERC orders spurred more transparency in transmission service and promulgated regional transmission planning. Order 764, issued in June 2012, required transmission operators to offer 15-minute interchange scheduling, mandated the use of wind power forecasting, and offered the potential for cost-recovery of integration charges on a case-by-case basis if other prerequisites were met. FERC has also held technical conferences to explore how to encourage flexibility in generation and to explore the potential need for capacity markets. Both issues are regarded as critical to address, as discussed in an IEA Wind Task 25 paper [157].

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77. See *http://www.nerc.com/comm/PC/Pages/Integration-of-Variable-Generation-Task-Force-(IVGTF)-2013.aspx* for more information.

78. Reliability standards are posted on NERC's web site at *http://www.nerc.com/pa/Stand/Pages/default.aspx*

IEEE

The Power and Energy Society of the Institute of Electrical and Electronics Engineers—now known simply as IEEE—has sponsored several wind power "super sessions" at its annual General Meetings. On alternating years, the November/December issue of *Power and Energy Magazine* is devoted to wind integration issues, with the 2013 magazine the fifth such issue. The Wind Power Coordinating Committee of the IEEE Power and Energy Society was chartered in 2005 and later expanded to include solar power. Expanded interest in wind integration is evidenced by the large and increasing number of wind-related research papers in journal publications. In addition, the *Journal of Sustainable Energy* was launched in 2010 and is devoted to wind power and other renewable technologies. There has been a significant increase in journal articles related to wind integration in the years leading up to 2013.

2.7.6 Conclusions

The electric power network operates reliably with high wind contributions (10% and higher), with minimal impacts on network operating costs. Many sites with the nation's best wind energy resources have minimal or no access to electrical transmission facilities. System operators are implementing methods to accommodate increased penetration of wind power. The experiences of grid operators that already have large amounts of wind power can benefit operators in areas where wind will expand over the coming decades. Some key lessons learned from experience with wind that confirms the results of integration studies are:

- Sub-hourly dispatch and interchange make it easier and less expensive to integrate high penetrations of wind power.
- Market designs have continued to evolve. Wind power is now part of the energy market and the security-constrained economic dispatch.
- Additional market features—such as look-ahead dispatch or other means to incentivize flexibility—are being implemented or investigated.
- Operational coordination between balancing areas—especially small ones—can facilitate wind integration substantially, and the 15-minute scheduling promulgated by FERC Order 764 is helping achieve this.
- When incorporated into operational practice, more accurate wind power forecasts can help cost-effectively integrate wind power.
- Advanced wind turbine controls can provide reactive power support, synthetic inertia, governor response, and regulation, further augmenting power system flexibility and reducing the cost of using large amounts of wind generation.
- More operational flexibility is needed at high wind power penetrations. In some cases, this flexibility may already exist and can simply be deployed if sufficient incentives are in place—or this flexibility can be provided by the wind power plants themselves. In other cases, additional flexibility may be needed.
- Transmission upgrades or expansion may be needed to increase system flexibility or to access the best wind resources.
- In addition to physical flexibility, institutional and market characteristics might inhibit access to flexibility.

Section 4.5 of the *Wind Vision* roadmap discusses several actions related to wind integration and required to achieve the *Wind Vision Study Scenario* deployment levels, including:

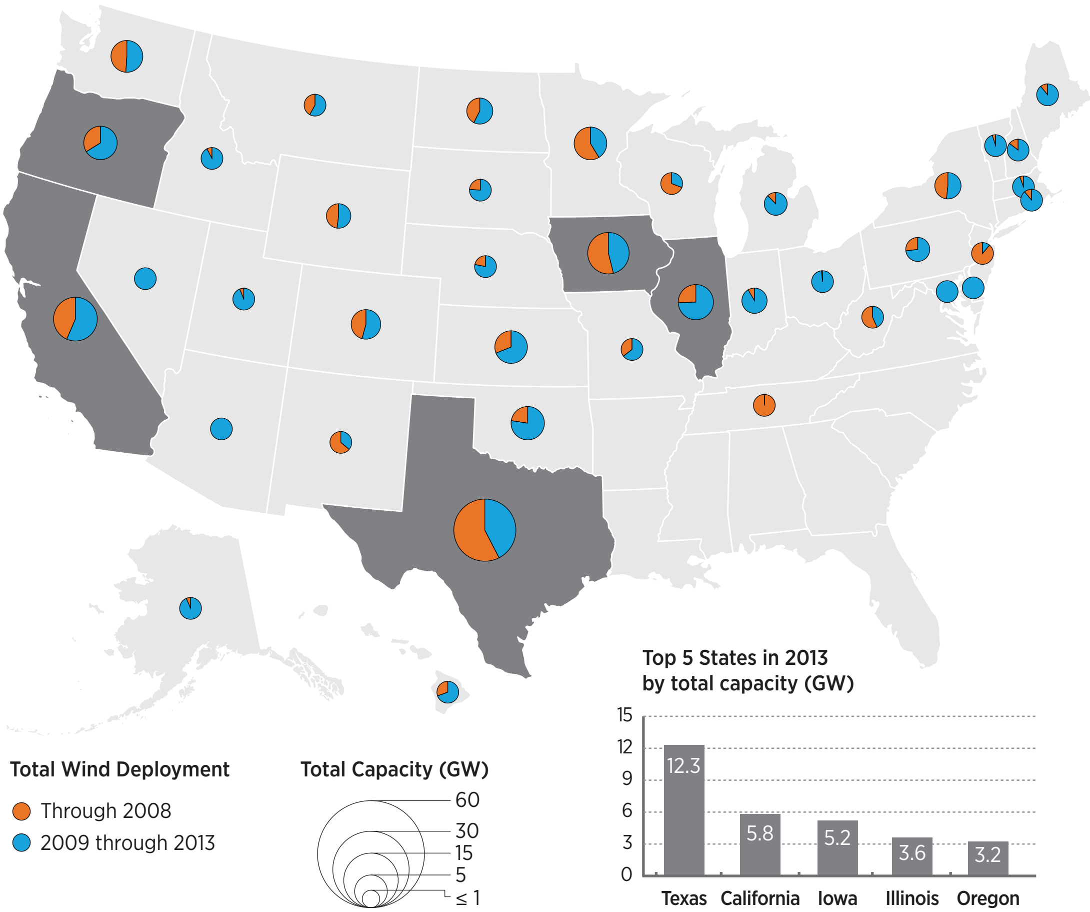
- Collaborating with the electric power sector to encourage sufficient transmission and provide for economically efficient operation of the bulk power system over broad geographic and electrical regions;
- Collaborating with the electric power sector to promote increased flexibility from all resources;
- Collaborating with the electric power sector to encourage operating practices and market structures that increase cost-effectiveness of power system operation with high levels of wind power;
- Optimizing wind power plant equipment and control strategies to facilitate integration;
- Developing optimized offshore wind grid architecture and integration strategies; and
- Improving distributed wind grid integration and increasing utility confidence in distributed wind systems.

2.8 Wind Siting, Permitting, and Deployment

Throughout the history of commercial wind power development, much has been learned about the impacts of wind turbines on their surroundings. Methods to address these impacts have been developed through investment in studies to understand impact risks. This research has led to improved siting practices and evaluation of avoidance and minimization measures, coupled with mitigation strategies. The wind power industry has implemented such strategies and continues to address siting and environmental issues.

Siting impacts have been evaluated and are manageable when project development is done responsibly.

Experience and research have shown that impacts of wind development on wildlife, public health, and local communities can largely be managed with avoidance, minimization, and mitigation strategies, as well as through communication.[79] These strategies include evolutions in siting practices, technology



Note: Distributed wind projects with less than 1 MW have been installed in all 50 states.

Source: National Renewable Energy Laboratory

Figure 2-43. Utility-scale wind deployment through 2013

79. The USFWS *Land-based Wind Energy Guidelines* [163] define mitigation, specific to the wind energy guidelines as "Avoiding or minimizing significant adverse impacts, and when appropriate, compensating for unavoidable significant adverse impacts." This is a broad definition which may cause confusion to readers without explicit understanding of impact assessment. Within the *Wind Vision,* additional terms such as 'impact avoidance' and 'minimization' are used to provide additional clarity. These are encompassed within the USFWS definition.

development, permitting processes, and operational procedures. With wind turbines over 1 MW in size deployed in many states by the end of 2013 (Figure 2-43), environmental and competing use concerns are increasingly important.[80]

This section provides detail on existing and continued efforts to address these concerns. Section 2.8.1 discusses public acceptance and environmental concerns associated with wind power including siting and permitting considerations, and public perception and community impact. Section 2.8.2 discusses the varied and complex regulatory environment affecting wind power.

2.8.1 Public Acceptance and Environmental Concerns

Wind generation capacity increased fivefold between 2008 and 2013. Although wind plant development has been concentrated in California, the Midwest, and Texas, wind turbines are operating in every region of the United States.[81] Wind turbines are being installed more widely and, in many cases, in closer proximity to people and communities. Advances in wind turbine technology are also facilitating expanded development interest in locations not considered previously, opening up the whole nation to potential wind development.

A March 2013 Gallup poll found that more than 71% of Americans think the United States should place more emphasis on wind power development. This percentage is slightly lower than related results for solar power, but above all other forms of domestic energy production. Favorable opinions of wind power were equal to or just below solar in all regions except for the South, in which residents slightly favor more emphasis on natural gas development [158]. More directed polling, especially when combined with informing survey recipients about the benefits and impacts of different energy options, typically results in high selections of wind [90]. Such polling does have regional variation, and results change when the questions focus on local development. Research specifically examining offshore wind development shows similar trends [159, 160, 161, 162].

The widespread use of distributed wind is significant and represents the leading edge of the interface between humans and wind power. Some states in the Southeast do not have large wind plants, but they all have some type of distributed wind system. The wide geographic spread of these distributed wind systems creates familiarity with wind turbines, reducing uncertainty and public concerns and paving the way for development of larger wind plants [164].

Local development helps support the view of wind as a viable technology that brings economic benefits, but it can also be a flashpoint for opposition. Focus groups conducted in New England and other areas show people's views of wind are dependent upon their local surroundings and communities [165]. Studies demonstrate that when wind project development includes active community engagement, public reactions are more favorable [165, 166].

Rapid increases in wind development have been accompanied by the formation of anti-wind organizations. These typically small and vocal organizations address local concerns regarding wind development, and express a desire to provide an alternative viewpoint. Open debate can eventually lead to stronger community buy-in as concerns are addressed. The challenge, however, is ensuring that information from both sides is fact-based, accurate, scientifically defensible, and accessible. A failure to reach these standards can cause delays or failures in wind permitting and development processes, and even ordinances and legislation that affect wind development based on poor understanding of potential impact.

Environmental Impacts of Wind Deployment

As with any form of energy generation, wind power development and operation can have impacts to the natural surroundings. Environmental impacts most commonly associated with wind development and operations are addressed in the following section.

The wind industry has invested significant resources to investigate and predict impacts to wildlife and to avoid, minimize, or compensate for these predicted impacts as appropriate. As is true of all energy sources, electricity from wind power does have impacts to wildlife. Specific wildlife concerns for wind are collision mortality of birds and bats (direct

80. Although not reflected in the figure, smaller distributed wind systems have been installed in every state.

81. As reflected in Figure 2-41, the Southeast does not have wind turbines greater than 1 MW as of 2013. The region does, however, have smaller distributed wind installations in operation as of 2013.

impacts to individuals) and indirect effects associated with habitat fragmentation and displacement of sensitive wildlife species [167]. Some examples of initiatives that have improved understanding of impacts of wind power on wildlife and provided measures to reduce those impacts include:

- U.S. Fish and Wildlife Service (USFWS) Wind Turbine Guidelines Federal Advisory Committee. Formed by the USFWS, this committee facilitated agreement among the industry, USFWS, state wildlife officials, conservation organizations, science advisors, and tribes on recommendations for dealing with wind power. This consensus served as the basis for the USFWS *Land-based Wind Energy Guidelines* [163], the most extensive set of wildlife-related guidelines developed for an energy industry as of 2013.
- In 2003, the wind industry partnered with federal agencies and the largest bat conservation organizations to found the *Bats and Wind Energy Cooperative*. In 2008, the wind industry helped found the *American Wind Wildlife Institute (AWWI)*, a partnership between wind power companies and the nation's largest science-based conservation and environmental groups. AWWI invests in applied scientific research to reduce uncertainty and develop minimization and mitigation strategies.
- The *National Wind Coordinating Collaborative* Wildlife Workgroup, facilitated by AWWI, is a joint effort of the wind industry, federal conservation agencies, other industry representatives, state officials, and conservation groups that conducts outreach on wind wildlife science and conservation.

Despite these efforts, uncertainty remains regarding the impacts of wind power development on wildlife. One challenge still to be addressed is the relationship between pre-construction activity and post-construction impacts, particularly with respect to bird and bat collisions [168]. Solutions to address this challenge are in development.[82] Regardless, the process of siting wind power plants has evolved significantly since the early days of the industry, when little was known about the interactions between wildlife and turbines. Further progress can be made with increased information sharing and peer-reviewed, applied studies that reduce uncertainty and establish solutions to minimize and mitigate risk and impacts to wildlife.

Impacts on Avian Species

While collisions with wind turbines are associated with bird mortality, mortality rates for birds at land-based wind plants average between three and five birds per MW per year, and no plant has reported an average greater than 14 birds per MW per year [169, 168, 170, 171]. Songbirds account for approximately 60 percent of all bird collision mortality [168], but current mortality levels constitute a very small percentage, typically <0.02%, of the total populations of those species [172, 173, 169, 174]. The more recent studies by Erickson et al. 2014 [169] and Loss et al. 2013 [171] support the conclusion that bird mortality is lower than earlier reported estimates. Overall, bird collision mortalities are low relative to other human-related bird mortalities (Table 2-8).

Table 2-8. Estimated Annual Bird Mortality Rates from Collisions with Engineered Structures

Structure	Average Mortality Rates (million birds/year)
Wind turbines	0.2[a]
Communications and other towers	6.8[b]
Power lines	130[c]
Buildings	300–1,000[d]

a. Source: Loss [171]
b. Source: Longcore [175]
c. Source: Erickson [169]
d. Source: Loss [171]

Eagles

Eagle mortality rates at some wind power plants have been higher than anticipated, particularly at older plants such as the Altamont Wind Resource Area in California, and this creates the impression that large numbers of eagles are at risk at all wind power plants. Early wind development in areas like Altamont experienced high eagle mortality.[83] As wind power has matured, however, the wind industry and regulatory agencies have been working to reduce impacts by

82. See AWWI's Information Center at *www.awwi.org*.

83. More information about avian mortality at early wind plants can be found in the proceedings of National Avian-Wind Power Planning Meeting held in July of 1994 to discuss this important topic. A link to the proceedings can be found at *http://qa.gpp.reisys.com/proceedings-national-avian-wind-power-planning-meeting-lakewood-colorado-july-20-21-1994*. A second meeting was held in September of 1995 to discuss research topics to address mortality issues, the proceedings for this meeting can be found at *https://nationalwind.org/research/meetings/*

modifying siting and operations procedures. Changes in wind turbine technology such as the use of taller tubular towers and slower rotor turbines have also reduced raptor impacts in locations such as Altamont [172]. This change is documented by the reduced numbers of raptor fatalities resulting from repowering at Altamont [170]. While eagles do occasionally collide with wind turbine blades, data indicate this is actually a rare event. As of 2014, however, there were no systematic, unbiased estimates of the relative frequency and magnitude of the various sources of eagle mortality, including wind power development. This gap can make it hard to predict the relative impact from expanded wind development.

That said, Pagel et al. (2013) [176] report 79 golden eagle fatalities and six bald eagle fatalities at wind power plants other than Altamont since 1997. This includes one bald eagle fatality at a single storm-damaged turbine on a wildlife refuge. Although Pagel et al. consider these numbers to be an underestimate, a survey of publicly available data on bald and golden eagle fatalities from anthropogenic causes (e.g., power lines, vehicles, lead, etc.) indicates that fatalities at wind plants are a small percentage of total annual mortality of both bald and golden eagles [177]. All impacts are assumed to be cumulative,[84] and expanded wind development could result in population concerns for certain regions where populations are already under stress. The eagle take[85] permit process, however, requires any losses of bald and golden eagles at wind farms to be offset by reducing mortality from other existing, unmitigated sources of eagle mortality. This stipulation ensures there is no-net-loss to eagle populations.

The USFWS enforces the Endangered Species Act (ESA), Migratory Bird Treaty Act (MBTA), and the Bald and Golden Eagle Protection Act (Eagle Act). In March 2012, USFWS issued a document outlining voluntary guidelines to help project developers avoid and minimize the impacts of land-based wind plants on migratory birds and other species of concern and their habitats [163]. Adherence to the Wind Energy Guidelines does not relieve any individual, company, or agency of its responsibility to comply with regulations such as permitting obligations pursuant to the ESA, Eagle Act, or MBTA, or obtaining a permit. The USFWS, however, will take adherence to the guidelines "into account when exercising [enforcement] discretion with respect to [a] potential referral" under the MBTA [163].

The Eagle Act provides a strict level of protection for both bald and golden eagle species, and, as mentioned previously, USFWS has instituted a "no net loss" policy for golden eagles. This policy requires developers to offset every golden eagle killed at a wind plant by reducing mortality from another source or by increasing eagle productivity. In April 2013, the USFWS released its "Eagle Conservation Plan Guidance Module 1 – Land-based Wind Energy Version 2" [178]. The guidance recommends conservation practices for siting, construction, and operations of wind power plants that can support developers to obtain eagle take permits in compliance with the Eagle Act. Permit regulations require wind plants to show that any take is unavoidable after adopting avoidance and minimization measures referred to as "advanced conservation practices." Because of the absence of appropriate data, however, USFWS has yet to finalize any advanced conservation practices. There are also permit uncertainties with respect to risk assessment methodologies, assessment models, and the available compensatory options for an unavoidable take. While the current regulations were originally promulgated in 2009, only one permit has been issued to a wind power plant through 2014, reflecting this ambiguity.

Prairie Chicken and Sage Grouse

It has been hypothesized that an operating wind power plant and related habitat disturbance could displace certain avian species and cause potential population decline. As of 2013, data for this theory are inconclusive. Certain species of prairie grouse—in particular, greater sage grouse and both greater and lesser prairie chickens—are thought to avoid breeding sites in the proximity of tall structures, but few

84. Although the impact of a specific wind plant is expected to be low compared to other anthropogenic cause, in areas where eagles are already under stress the sum of all of these impacts, especially in the light of expanded wind deployment as depicted within this Vision scenarios, may be a reason of concern for populations in specific regions.

85. Under the Bald and Golden Eagle Protection Act, the term "take" includes, "pursue, shoot, shoot at, poison, wound, kill, capture, trap, collect, molest or disturb" (16 U.S.C. 668c; 50 CFR 22.3). "Disturb" means "to agitate or bother a bald or golden eagle to a degree that causes, or is likely to cause, based on the best scientific information available, 1) injury to an eagle; 2) a decrease in its productivity, by substantially interfering with normal breeding, feeding, or sheltering behavior; or 3) nest abandonment, by substantially interfering with normal breeding, feeding, or sheltering behavior."

published studies have tested this hypothesis with specific regard to wind power plants [173, 179]. Other studies [180, 181] have questioned whether the impacts are from the tall structures themselves, versus other factors like road noise. Recent research specific to greater prairie chickens indicates the species is not strongly affected by wind power development. Several published studies focusing on central Kansas show a slight reduction of breeding areas near turbine development, but no negative effect on nest site selection and—in some cases—increased female survival rates [182, 183].

Many prairie chicken and grouse grassland habitat areas across the Midwest and West have been identified as potentially ideal for development of wind power and other energy plants. Stakeholder groups generally agree that there is a need to better understand the potential and actual impacts of development of wind power plants on prairie chickens and sage grouse in order to identify possible mitigation approaches. Several groups—including the National Wind Coordinating Collaborative, AWWI, and the Bureau of Land Management (BLM)—are funding research to more fully understand the potential impact wind development has on the populations of these species [184]. Land use and conservation planning efforts undertaken by the BLM and state wildlife agencies, may restrict or eliminate the potential for wind energy development in the historic range of these species in order to reduce the likelihood for ESA designation. The benefit, however, is that these efforts also may provide clarity on wind development opportunities over the long-term.

Whooping Crane

Recognizing that some of the best wind resources in the country overlap with the migration corridor of the Whooping Crane, a group of 15 developers worked in collaboration with the USFWS and state agencies to develop a multi-species regional programmatic Habitat Conservation Plan (HCP).[86] This HCP covers wind power development activities for an area extending 1,500 miles north/south—from the Texas coast to the Canadian border—and 200 miles wide This HCP is anticipated to provide legal certainty for wind developers, while including essential planning and conservation measures.

Impacts on Bat Species

Bat mortality associated with wind plants can be higher than bird mortality and shows greater variation both within and among regions. Two wind plants in the eastern United States have reported averages of up to 30 bat fatalities per MW per year, but other plants in the East have reported one to two bats per MW per year [185]. Migratory tree bats constitute the majority of bat fatalities accounted for at wind plants. A lack of knowledge about population size for these species and about the impact of non-wind-related issues—such as white nose syndrome, habitat loss, conventional energy development impacts, and other anthropogenic impacts—have raised concerns that tree bats may be unable to sustain current mortality rates [186]. Without this baseline information, however, there is no way for the scientific community to come to a conclusion either way. Research is identifying discernible patterns in bat mortality at wind power plants, including a correlation between fatalities and migratory and mating behaviors.[87] In 2011, the USFWS released "Indiana Bat Section 7 and Section 10 Guidance for Wind Energy Projects" [187] to help USFWS biologists assess the impacts of wind power plants on the endangered Indiana bat. These guidelines are considered an interim step needed until there is a more complete understanding of Indiana bat-wind plant interactions [178]. The number of bat species being considered for ESA listing by the USFWS is increasing as of 2013, due largely to White-nose syndrome as well as anthropogenic causes. Listing of these species will result in federal oversight of wind-wildlife issues on private lands and could complicate the permitting and deployment process for new wind systems, as well as potentially impact operations in the existing fleet.

Recognizing the need to address conservation concerns regarding bat impacts, the wind industry is engaged with USFWS, state wildlife agencies, and other stakeholders to develop a multi-species, multi-state regional HCP to cover activities related to wind energy development and operations throughout the eight-state Midwest region. As of 2014, the wind industry and scientific and conservation communities were testing promising methods that have reduced

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86. HCPs under Section 10(a)(1)(B) of the ESA provide for partnerships with non-federal parties to conserve the ecosystems upon which listed species depend, ultimately contributing to their recovery. HCPs are required as part of an application for an incidental take permit and describe the anticipated effects of the proposed taking; how those impacts will be minimized, or mitigated; and how the HCP is to be funded.

87. *www.fort.usgs.gov/BatsWindmills/*

bat mortality by more than 50% in field testing at several sites [185]. Continued investigation and data collection will support enhanced understanding that can help wind developers avoid and minimize bat mortality.

Impacts on Other Species

Impacts of wind development to wildlife species other than bats and birds are not well understood [167]. As discussed later in this section, studies indicate that direct loss of habitat from turbine pads, access roads, and transmission is a small percentage of the total wind plant area. Other potential impacts from land-based wind including indirect effects such as displacement or demographic decline owing to disturbance or the fragmentation of suitable habitat need to be determined and verified by additional research. Although doing so is outside the focus of the *Wind Vision*, the potential impacts of wind development should be evaluated within a construct that considers the potential environmental impacts of other energy development.

Impacts of Offshore Wind Development

Wildlife concerns associated with offshore wind include effects on migratory birds, marine mammals, essential fish habitat, and protected and threatened species such as sea turtles. Benthic communities, such as warm and cold water corals that have endangered or threatened status would also need to be considered. Bird strikes are likely to be a key offshore wind regulatory issue in the United States, but experience from Europe indicates that migratory bird collisions may occur at a lower rate for offshore than for land-based wind [188]. According to published literature, most seabirds and waterfowl tend to fly below the rotor swept area, while nocturnally migrating land and shorebirds usually fly above the rotor swept area [189]. Additional concerns include offshore wind plants displacing waterfowl from foraging habitat or acting as barriers along migratory pathways. Initial offshore surveys along the East Coast indicate avian activity is more prevalent closer to shore and lower beyond 10 miles from shore [190]. Given the current lack of existing general data, BOEM provides guidance for avian surveys required for the project review approval process.[88]

Sufficient—though limited—data suggest that bats migrate offshore and use islands, ships, and other offshore structures as opportunistic or deliberate stopover sites. Bats may also forage offshore during migration, perhaps to avoid competition or to exploit certain food sources [191]. The potential impact of offshore wind development on bat species of interest is, however, unknown, and more directed research is needed.

The construction and operation of offshore wind plants also pose the risk of harassment or injury under the Marine Mammal Protection Act and the ESA, particularly during construction and maintenance. Developers of offshore wind will likely be required to apply for "take" permits under the ESA and/or incidental harassment authorization for harming marine mammals under the Marine Mammal Protection Act (NOAA Fisheries). At a minimum, developers will be responsible for consulting with appropriate parties under Section 7 of the ESA.[89]

The ESA offers a broad definition of "take," including sound-related harassment. As such, offshore wind developers face particular concern for the North Atlantic right whale. With a total population of about 450, the right whale is listed as endangered under the ESA and as a depleted species under the Marine Mammal Protection Act.[90] As of 2014, there are few definitive studies correlating the level of sound from operation of wind turbines with behavioral changes in marine mammals. Certain geophysical surveys and pile driving during construction of offshore wind plants pose the risk of auditory harassment or injury—as defined by the Marine Mammal Protection Act and the ESA [192]—to marine mammals, sea turtles, and some fish. Survey and construction vessels also pose collision risks for whales, other marine mammals, and sea turtles [192]. To help address various concerns about marine mammals, BOEM provides guidance for pre-construction surveys to establish a baseline for the presence and activity of marine mammal species.[91]

88. BOEM's constructions and operations guidance is available at: *http://www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/*

89. Section 7 of the ESA provides guidance for interagency cooperation on issues related to the ESA. A summary of Section 7 is available at *http://www.fws.gov/endangered/laws-policies/section-7.html*.

90. NOAA Fisheries, *www.nmfs.noaa.gov/pr/species/mammals/cetaceans/rightwhale_northatlantic.htm*. Accessed June 4, 2014.

91. *http://www.boem.gov/National-and-Regional-Guidelines-for-Renewable-Energy-Activities/*

Pre-construction baseline wildlife surveys and ongoing monitoring and mitigation, including curtailing construction activities upon the approach of marine mammals, can help reduce the risk of offshore wind development to such species. BOEM requires measures to protect Northern Atlantic right whales from collisions and from survey and construction noise as Standard Operating Conditions of each new offshore wind lease [193]. [92,93]

Siting and Permitting Mixed Use Considerations

Beyond the local environmental impacts of wind deployment, there are additional considerations that need to be addressed as part of state or local permitting requirements. The following highlights the most important of these permitting questions.

Sound

Turbine sound is typically one of the greatest nuisance impacts associated with wind power [166]. As of 2013, however, global peer-reviewed scientific data and independent studies consistently concluded that sound from wind plants has no direct impact on physical human health [194, 195, 196, 197, 198].

For example, the Australian National Health and Medical Research Council issued in 2010 a draft report on the results of an independent review of available scientific literature examining the relationship between wind power and health. The Council found "no consistent direct evidence that exposure to wind plants was associated with any health outcome" and noted that the "few associations reported by individual studies could have been due to chance" [197].

In 2012, the Massachusetts Department of Environmental Protection and Department of Public Health commissioned a panel of experts in public health, epidemiology, toxicology, neurology and sleep medicine, neuroscience, and mechanical engineering to analyze health effects of turbines, including those resulting from noise. The panel reviewed existing studies, including both peer-reviewed and non-peer-reviewed literature. The panel found that the strongest epidemiological study suggests there is no association between noise from wind turbines and measures of psychological distress or mental health, and that none of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain or stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headaches or migraines [199].

Additional studies, including one by a scientific panel convened by AWEA and the Canadian Wind Energy Association, have also concluded that sound from wind turbines does not cause negative health impacts [200].

While scientific evidence does not demonstrate any health risks, some residents living close to wind turbines have expressed annoyance attributed to turbine sound [201]. Some studies have documented annoyance and confirmed its correlation with turbine sounds, but have also found correlations with attitudes towards and visibility of specific wind plants [202, 203, 204]. Two studies [205, 206] have documented that complaints associated with wind turbine noise can be impacted by the availability of information—accurate or inaccurate—about the potential impacts of wind noise. This study included the finding of physical symptoms in control groups not subjected to such noise. Even with this research, however, turbine manufacturers are working to reduce mechanical noise (e.g., from generators and gearboxes) as well as aerodynamic noise to help preempt concerns.

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92. The Conservation Law Foundation, Natural Resources Defense Council, National Wildlife Federation and Deepwater Wind, LLC, reached an agreement in May 2014 to implement additional protections for endangered North Atlantic right whales during pre-construction activities for the 500-MW Deepwater ONE offshore wind plant, which will be developed off the Rhode Island and Massachusetts coasts (*http://www.clf.org/right-whales-offshore-wind*). The agreement reduces the threat to right whales by restricting meteorological tower construction and other site activities during the peak foraging season, when whales venture to southern New England waters to feed. During other times of the year, when the whales frequent the area less, the activities may proceed under additional protective measures. These measures include enhanced real-time human monitoring for whale activity in the site area; restriction of pile driving activities to daylight hours when whales can be spotted; use of noise-reducing tools and technologies; and a lower speed limit for vessels during periods in the spring when North Atlantic right whales have been known to frequent Rhode Island Sound. A separate October 2013 agreement between Deepwater Wind and the Conservation Law Foundation restricts all construction activities for the 30-MW Block Island Wind plant foundation during the month of April.

    In 2012, a coalition led by the Conservation Law Foundation, the Natural Resources Defense Council and the National Wildlife Federation, working with Deepwater Wind, Energy Management, Inc. (owner of Cape Wind in Massachusetts), and NRG Bluewater Wind, drafted a similar set of protective measures that developers agreed to implement in the Mid-Atlantic Wind Energy Areas, which stretch from New Jersey to Virginia.

93. *http://www.boem.gov/Commercial-Wind-Leasing-Offshore-Massachusetts/*

Shadow Flicker

Shadow flicker results when the rotating blades of wind turbines cast moving shadows on the ground or on structures [207]. The phenomenon exists for some daily period of time at all wind sites if there is enough sunlight and the blades are rotating, but is more acute at high latitudes. In high latitude locations, the sun is in a low position on the horizon for a greater amount of time, resulting in a longer potential wind blade shadow. Shadow flicker is also more common in early morning and evenings, and can vary relative to surrounding structures and vegetation.

Nuisance complaints of flicker include anecdotal reports of nausea and vertigo, and the IEA [166] identifies shadow flicker as a nuisance. A study completed for the U.K. Department of Energy and Climate Change, however, concluded that, "…the frequency of the flickering caused by the wind turbine rotation is such that it should not cause a significant risk to health" [208]. Though the relationship between flicker and epileptic seizures has been questioned, there is no scientific evidence to support these claims. The strobe rates generally necessary to cause seizures in people with photosensitive epilepsy are 5-30 flashes per second [209], and utility-scale wind turbine blades cannot rotate this quickly.

The potential impact of shadow flicker is dependent on micro-siting. Wind plant designers often model where shadows might fall throughout the year in order to minimize potential impact on homes or structures. In many cases, setback distances in community ordinances and safety and sound setbacks for utility-scale wind projects usually place turbines far enough from structures to avoid flicker impacts. Although some controlled level of flicker is generally accepted in planning documents [207], mitigation measures can also be taken to reduce potential impacts. These measures may include flicker-specific setbacks, vegetative buffers, or the curtailment of the turbine during times of highest impact.

Land Use

There are several ways to consider the amount of land actually required to implement a wind plant. This requirement is project- and location-specific, but land use of wind plants can generally be broken into the following impact zones:

- **Leased Land:** This designation applies to all land that may be owned or leased for a proposed or operating wind plant. This is typically the largest potential area and may include land that is optioned by the developer but will not be developed as part of the wind plant. In almost all cases, this land will have multiple uses and only the wind development rights will be subject to the lease.
- **Plant or Facility Boundary:** This accounts for the legal boundary of the wind plant and may represent landowners who are being compensated for use of land related to a wind project. Because of the spacing of wind turbines, most of this area is not directly impacted by the plant and may have other economic uses, such as farming or ranching. Wind plants are not typically fenced because of their size, but restricted access gates or other access limitations are often used. Research indicates that the average plant boundary for a land-based wind plant[94] is 0.34 km^2/MW (85.24 acres/MW) [210]. For offshore wind plants, a range of values between 0.20 and 0.60 km^2/MW (49.4 to 148.2 acres/MW) have been proposed for projects along the Eastern seaboard [70, 71, 72, 73].
- **Land Transformation Areas:** This is the area of land that is considered disturbed from an environmental perspective. This area of disturbance will vary widely, depending on local ground cover near a wind plant. For example, in forests, more clearing may be required for roads, transmission upgrades, and safety setbacks, causing a greater impact then the same plant installed at a non-forested site. An analysis, using satellite images of land-based wind plants, completed by the U.S. Geological Service indicates that land transformation varies between 0.0011 and 0.043 km^2/MW (0.27–10.63 acres/MW), depending on considerations such as land cover (forest or farmland) and topography (Mesa or flat) [211].
- **Wildlife Disturbance Areas:** This represents the area within which wildlife may be disturbed. The wildlife disturbance area depends on habitat type and needs of the species within a project location, as well as sensitivity to human activity. In locations with wide-ranging species, such as eagles, the potential disturbance area can be quite large as compared to a site with narrow-ranging species,

94. The average value provided by Denholm is based on the project defined facility boundary for 161 specific projects totaling 15,871 turbines and 25,438 MW of installed capacity. The specific facility boundary for a specific project however can vary greatly from this value as is described in the full report.

such as turtles or salamanders, or those that are not susceptible to human disturbance.

- **Temporarily Disturbed Land:** The "temporarily disturbed" designation applies to the land area that will be used during construction of a wind plant but then returned to its original or an improved condition. This would include laydown yards for receiving the wind turbines and towers, crane pads, and electrical cable trenching. The expected temporary construction impact of a wind plant is about 0.007 km^2/MW (1.73 acres/MW), larger than the operational impact [210].
- **Operational Impacted Land:** This is the amount of land used for permanent structures such as access roads, tower foundation pads, and transformer pads. Operationally impacted land cannot be used for other purposes during the life of the wind plant. The expected operational impact of a wind plant is about 0.003 km^2/MW (0.74 acres/MW) [210]. The disposition of the wind plant after its operational life is determined by the contractual arrangements for decommissioning, but could include the removal of all surface features of the turbine foundation, roads, and other facilities. Complete removal may not be required if the land could be used to develop new wind assets through repowering [29]. The operational boundaries for offshore wind projects and how these boundaries will impact other uses have not been fully resolved and may vary based on plant location and jurisdiction.

With the exception of the range designated for the *Plant or Facility Boundary*, there are no specific numbers available for the impact zones created by offshore wind. The primary reason is that no U.S.-based offshore wind plants have been implemented, and issues around access and alternative use are still largely undefined. Within the boundaries of offshore wind plants, some restrictions are likely—such as changes to certain fishing practices—though other activities will still be permitted. Unlike land-based wind development, which has largely been undertaken on private land, offshore wind development will take place in public waters. This will require a formalized process to determine what additional water area uses will be acceptable.

The idea that wind power consumes large tracts of land results from a misconception that the entire land area "encumbered" by a wind lease is isolated from other uses, which is not the case. Although there are different ways to define the footprint of a wind plant, about 99% of land around a wind plant can be used for other activities, such as farming, ranching, and recreational activities [210]. Additional siting considerations—such as access road layout, land use during installation, potential long-term farming improvements, and current irrigation systems—need to be incorporated into all land lease contracts but are typically designed to mitigate the long-term impact to other land uses.

Radar and Aviation

For nearly a decade, government agencies have sought to balance the nation's need for new energy resources and the demands of critical air surveillance missions. Issues considered include flight safety, aerial monitoring of severe weather conditions, commerce, and control of U.S. borders and skies. While the federal government has worked to develop policy that ensures wind turbines and radars can co-exist, air surveillance and weather radars are impacted by wind power plants [212]. Some interference effects of wind turbines on radar systems include the inhibition of target detection, the generation of false targets, interference with target tracking, and hindrance of critical weather forecasts. In extreme cases, turbines have also caused significant electromagnetic issues. Interactions between wind turbines and aviation can impact government missions such as homeland security and defense (including training facilities and test ranges), air traffic control, flight safety operations, weather forecasting, maritime patrol, law enforcement, communications, and infrastructure protection. Potential issues have been addressed though siting requirements implemented by several federal agencies.

In 2008, the only widely used mitigation strategy was to ensure that wind turbines were located out of the line of sight of any radar. As a means to develop alternative mitigation strategies, the Interagency Field Test and Evaluation (IFT&E) program was implemented by the DOE, U.S. Department of Defense (DoD), U.S. Department of Homeland Security, and the Federal Aviation Administration's (FAA) with collaboration and assistance from NOAA with the goals to characterize the impacts of wind on air surveillance radars, assess near term mitigation strategies and increase technical understanding to advance development of long term mitigation strategies [212]. Through the implementation of a series of flight based field tests, several potential mitigation strategies were considered and show to improve, but not eliminate the impacts of wind turbine operation in proximity to wind farms. Infill radars to restore a loss in radar coverage in the vicinity of a wind plant and replacement radars, upgrading the identified radar technology, were both shown to improve detection performance. Other approaches including wind turbine-specific technologies such as radar-absorbing materials or coatings, structure shaping, wind plant layout design, and wind turbine-to-radar data-control schemes have also been considered but were not included in field based assessments completed to date. Several radar and software upgrades were evaluated with little documented impact, although alternative upgrade approaches may be more successful [212].

Federal agencies have instituted programs to identify new capabilities and help address radar issues related to wind turbines. These include the North American Air Domain Awareness Surveillance Analysis of Alternatives, the NOAA Multi-Function Phased Array Radar initiative, and the FAA's NextGen Surveillance and Weather Radar Capability program. Other ongoing government radar stakeholder activities include initiatives that leverage the success of the U.S. Interagency Field Test and Evaluation program through the development of a national Wind-Radar Interference Strategic Planning framework (to track mitigation capability research, development, and strategies), as well as implementation of the interagency agreement to execute a Pilot Mitigation Project Initiative (minimizing industry and government risk in accepting industry funded mitigation solutions).

Improvements in the two primary review processes, the NOAA WSR-88D NexRad review process and the DoD's role in the FAA Obstruction Evaluation/Airport Airspace Analysis review process, have led to enhanced wind permitting procedures. NOAA developed an improved build zone database accessed through the DoD Preliminary Screening Tool on the FAA Obstruction Evaluation/Airport Airspace Analysis website. The FAA website also includes a capability to engage NOAA representatives in an early notification process via links to the National Telecommunications and Information Administration, NOAA's review process clearinghouse for wind-radar evaluations.

The DoD has revised its review process significantly by establishing the DoD Siting Clearinghouse, which provides a "one-stop-shop" for comprehensive, expedited evaluation of energy plants and their potential effect on DoD operations. The Clearinghouse's formal review process applies to projects filed with the Secretary of Transportation, under Section 44718 of title 49, U.S. Code (FAA obstruction evaluation process). It also applies to other projects proposed for construction within military training routes or special use airspace, whether on private, state, or federal property such as that managed by BLM. Operational impacts of wind turbines on DoD missions are determined by several DoD organizations in parallel. The DoD Siting Clearinghouse acts as the conduit between the FAA's Obstruction Evaluation Review Process and the wind developer. DoD uses two types of reviews, a formal review and an informal review.[95]

All land-based construction more than 200 feet tall, including wind turbines, needs to be assessed under the FAA's Obstruction Evaluation. FAA-approved lighting is also mandatory for structures over 200 feet, and updated lighting regulations are being considered for structures taller than 500 feet. Specific FAA regulations place additional requirements to site turbines in close proximity to airports. These regulations are complex and have many dependent requirements—such as the type of airport (commercial, military, or private), local terrain variations, and type of approach (precision instrument)—but they generally limit structure height in proximity to airports and/or controlled airspace. Several mitigation options have been proposed to reduce possible effects of nighttime lighting. These include directional shielding, permission to light only some towers versus all, and the use of airplane detection technology that turns on lights only when aircraft are in the area.

Communications Systems

There are two categories of communications that need to be evaluated during design and permitting for wind plants: television and radio reception for neighboring residents, and local microwave tower interference. Transmission from radio or TV broadcast frequencies can be influenced by obstacles between the transmitter and the receiver. Modern wind turbines blades are made primarily of composite materials so there is usually minimal impact on the transmission of electromagnetic radiation, e.g.,

95. Details on each review can be found at *www.acq.osd.mil/dodsc/contact/dod-review-process.html*.

radio or TV signals. Revolving turbine blades sited directly between transmission sources and receptors, however, can interfere with TV reception. This can be rectified by replacing the existing antenna with a larger, more powerful one; adding a reception booster to the antenna; or switching to cable or a satellite service. These solutions are typically required to be procured by the wind plant owner and are usually a condition to local or state permits.

Interference with microwave-based line-of-sight communications is also a potential concern. Wind plant developers are required by state and local permitting agencies, as well as many financing companies, to perform a communications impact analysis or equivalent to demonstrate that pathways between communicating towers are unobstructed prior to having wind project construction or operational permits approved. If a potential obstruction is identified, mitigation options can be applied either at the wind plant or with the microwave towers.

General Safety

As with any machinery, wind turbines can fail and result in safety issues. Although no industry wide, reference quality assessment of catastrophic wind turbine failures has been completed, they are considered rare events with fewer than 40 incidents identified in the modern turbine fleet of more than 40,000 turbines installed in the United States as of 2014. Modern wind turbines represent a significant investment, and high priority is placed on regular maintenance to reduce the chances of catastrophic failure. Turbines are equipped with sensors and data acquisition systems designed to turn the turbine off when any unusual operational condition occurs, typically before a catastrophic failure. In order to protect nearby structures and public safety, local municipalities, counties, and state regulators define safety setbacks to guard against impacts in the unlikely event of tower collapse, blade throw, and ice shedding. In areas where turbine or blade icing may occur, additional safety-related conditions may be requested or required [213].

Marine Safety

BOEM requires a detailed navigational risk assessment of each proposed wind project area to determine how current vessel traffic patterns and density may change as a result of the construction and operations of an offshore wind plant. Developers need to evaluate if the siting, construction, establishment, operations, maintenance, and/or decommissioning of wind power plants might cause or contribute to obstruction of or danger to navigation and/or affect the traditional use of a waterway. The U.S. Coast Guard is responsible for ensuring navigational safety for commercial and recreational vessels under the Ports and Waterways Safety Act, which extends 12 nautical miles from the U.S. coast. Buffers and navigational routing measures around offshore turbines minimize the risk of collision with turbines at sea and mitigate safety concerns associated with equipment failure. Automated Identification System transceivers may also be installed on wind turbines or buoys to mark a particular wind plant boundary feature, and restrictions on transit through wind plant areas may be imposed during periods of reduced visibility.

Public Perception and Community Impact

The final area of consideration is how the deployment of wind plants impacts public and community perception. Although some of these overlap conceptually with potential impacts identified in other sections, the areas of concern in this section are discussed primarily at the community level.

Visual Impacts

Surrounding property owners and the community often express concern about the visual impact of a wind plant. While most other potential impacts of wind development can be measured or at least discussed in quantitative terms, visual impacts are more qualitative and based on an individual's appreciation of and interaction with their surroundings. In addition to referencing research about the visual impacts of wind power such as those summarized in the 2011 International Panel on Climate Change special report on wind energy and climate change mitigation (e.g., Wiser 2011 [84]), project developers and communities commission visual impact assessments that provide a better understanding of what turbines may look like against different landscapes.

Without clear standards or guidance on how these visualizations are structured, it is difficult to assess potential impacts. To help address this, a set of common protocols for visual impact assessments were implemented by the Clean Energy States Alliance [214]. DOE supported the resulting guide issued by the Clean Energy States Alliance, "A Visual Impact Assessment Process for Wind Energy Projects." This document offers aesthetic impact assessment review methodology and guidance for developers, planners, and regulatory decision makers, and includes suggestions for establishing a clear and consistent visual impact review process. Additional stakeholder discussions have also provided useful information on ways to engage with communities about the visual impact of wind power development [165]. Tools have been developed to provide state-of-the-art visual impact assessments, including video representation.

Aviation avoidance lighting has also been highlighted as a visual annoyance for wind turbine installations. Mitigation options have been proposed to reduce the potential effects of nighttime lighting and several are under FAA review. These include some of the options discussed in the Radar and Aviation section, such as directional shielding, permission to light only some towers, and the use of airplane detection technology.

Other factors related to aesthetics and wind development include guidelines from State Historic Preservation Offices[96] and systems for evaluating projects proposed on public lands. Some states have separate jurisdictions to review and approve projects proposed for public lands.

Property Values

Given the long history of concern about the potential impacts of wind development on property value, the body of peer-reviewed literature investigating such impacts is increasing. The seminal work in this area, with the largest data set, was conducted by LBNL. This work found no statistical evidence of adverse property value effects resulting from views of and proximity to wind turbines after the turbines were constructed [215, 216, 217, 218]. Other peer-reviewed and academic studies also found no evidence of post-construction effects across a variety of techniques and residential transaction datasets [219, 220, 221, 222, 223, 224]. Courts in Canada (Kerry v. MPAC 2012) and Wisconsin (Realtors et al. v WI PSC 2014) made determinations that evidence of property value impacts was not sufficient to warrant overturning previous decisions. Three working papers in the European Union, however, do report impacts to home values in Germany [225], Denmark [226], and the United Kingdom [227]. These results imply that, in the United States and Canada, post-construction effects of wind turbines on the value of surrounding homes either do not exist, are too small for detection, or are sporadic (resulting in a small average percentage), while effects in some European countries are more pronounced. Analysis in the United States has, however, found some evidence of potential property value effects after a wind plant has been announced but prior to construction [222, 221, 218].

Local Economic Development

Data related to utility-scale wind development demonstrates numerous positive economic impacts [91, 228, 229]. The 2011 Slattery study [91] estimated economic impacts from 1.4 GW of wind power development in four rural counties in west Texas. The total economic activity to the local communities was estimated to be nearly $730 million over the assumed 20-year lifetime of the wind plants, or $0.52 million per MW of installed capacity.

Social and economic benefits from distributed and community wind plants typically remain in the local community. Distributed wind turbines normally rely on a local small business to install or develop the wind turbine system. In locations with high electric retail rates or the threat of electric rate increases, energy produced by an on-site distributed wind installation can offset electricity costs, lowering operating costs for the system owner (e.g., a local business). An NREL study found that community wind plants have increased local employment impacts during both the construction and operations periods compared to plants developed by parties from outside the local area. These employment related impacts range from 1.1 to 1.3 times higher for the construction phase and 1.1 to 2.8 times higher in the operations phase [229].

Competing Uses

As of 2013, most wind turbines are installed on land that was typically used for other purposes prior to the wind installation. Wind development on private lands results in compensation to the land owner for the potential loss of use of the land; private landowners receive an estimated $180 million annually in land lease payments from wind project developments [9]. Development on federal and state properties (both land and water) poses complications, since installation of the plant may impose restrictions or otherwise impact uses for the area, but affected parties do not have legal grounds to any direct compensation. For

96. One example is the New York State Historic Preservation Office guidelines for the assessment of historic and cultural resources associated with the development of wind plant projects in the state, available at *http://www.nysparks.com/shpo/environmental-review/*.

example, commercial and recreational fisheries are part of the culture and economy of coastal communities but receive no direct compensation from offshore development in federal waters because royalties are only paid to the appropriate state and federal government.[97] Such communities will want clear and accurate information about whether and how a proposed plant will affect the species of fish they target, how they fish, or where they have historically fished. Shipping lanes and navigation have also played a role in the development of current leasing zones for offshore wind, but rules have not been finalized to govern use of leasing areas for other activities. Another example of public sites in which proposed wind plants may cause conflicts are offshore and land-based DoD firing ranges, flight training, and exercise areas. To the extent possible, the impact of wind development on competing uses should be understood prior to project initiation, and developers should coordinate with the local community, land use and regulatory agencies, and other stakeholders during project conception, development, construction, and operation.

Summary

Competing use, public acceptance, and environmental concerns for wind plants can be addressed through careful and considered siting, which should include open collaboration with the community and its leaders. This will facilitate increased public involvement and understanding of best practices for wind installations. Additional activities that have proven effective in enhancing understanding of wind siting concerns include:

- Stakeholder engagement, including proactive development and dissemination of publicly accessible information about wind impacts and benefits through publications, electronic and social media, workshops, and outreach;
- National, state, and regional efforts to gather, analyze, and distribute information; and
- National and regional independent or consensus-based organization(s) that have helped improve the scientific research, facilitated discussions on wind-related impacts, and provided negotiated paths for implementation of locally appropriate best practices.

2.8.2 Regulatory Environment

The regulatory environment for wind project development is varied and complex, with an array of federal, state, and local rules that create uncertainties in development timelines and project development success. As with almost any development project, permitting is required. Since the United States uses a dispersed model of development approval that is regulated at the state or local level, permitting requirements vary based on project location and size. These variances, combined with differing levels of public involvement, can create a challenging regulatory environment. Section 5.5 of the *20% Wind Energy by 2030* report provided an overview of the siting and regulatory framework for wind power projects, highlighting related permitting processes and regulations.

The wind power community has addressed substantive siting and regulatory issues, but continued work is needed to reduce uncertainty and streamline siting and permitting.

While variance still prevails, local and state regulations are evolving as more wind opportunities are explored and deployed across the country. In January 2012, the National Association of Regulatory Utility Commissioners published a report summarizing land-based wind power siting and zoning practices in all 50 states and the District of Columbia [207]. The primary decision-making authority for land-based wind project permitting resides with local governments (known as Home Rule) in 26 states, and state governments (referred to as Dillon's Rule) in 22 states. Other states use shared local and state responsibility for permitting. The National Association of Regulatory Utility Commissioners report provides recommendations on siting and zoning best practices to help guide states in their processes. Other organizations have created similar guidance documents for wind power development, including The American Planning Association [230] and AWEA [231].

While several states have permitting processes for utility-scale land-based plants, few address distributed wind. Some states with distributed wind-focused grant programs have a defined permitting process for

97. Based on Code of Federal Regulations, Title 30, Chapter V, Subchapter B, Part 585, Subpart E, Section 585.540, wind projects between 3 nautical miles from the state boundary (typically between 3 nautical miles and 6 nautical miles from the coastline for all states except Texas) receive 27% of all federal royalties from offshore wind development. Beyond 6nm all royalties are retained at the federal government.

projects receiving such grants. This lack of established standards or familiarity with distributed wind on the part of authorities can create an inefficient and costly project development process for installers who need to navigate state, local, and utility regulations as well as educate officials during the process. DWEA published in 2012 a model ordinance and guidelines to lead local governments through the process of adopting wind turbine ordinances for distributed applications [77]. The Interstate Renewable Energy Council issued an update to its Model Interconnection Procedures in April 2013 [232] based on evolving best practices and state rulemakings across the country, particularly in California, Hawaii, and Massachusetts.

State and federal agency compliance is needed for all wind power plants in order to protect historic and cultural resources, wildlife, and wetlands and watercourses. FAA approvals are often necessary as well due to the typical height of larger wind turbines. Additional federal oversight is required for projects that include federal funding, permitting, or are sited on public land. For instance, wind plants proposed for public lands or otherwise subject to federal permitting trigger the National Environmental Policy Act. The Act requires thorough analysis of the impacts of the plant and alternatives to the proposal, as well as public participation in the permitting process. Larger projects may involve a combination of varying land types or organizational jurisdictions, such as an offshore wind project that straddles state and federal waters. Such combined requirements may further complicate the permitting process.

The diversity of requirements, authorities, and decision makers can make it complicated and time-consuming to obtain permission for construction and operation of a wind plant. While federal regulations are standardized at the national level, statutes are applied and enforced through state or regional offices or departments within agencies. Regulations or standards vary to meet local needs and policies. Because of this, there is no uniform permitting process for land-based or offshore wind, and information required for permitting can vary from location to location. The development process can be further complicated by a lack of coordination among local, state, and federal regulators. Wind power has expanded rapidly in the decade leading up to 2014, causing agencies to play catch-up in gaining the understanding and experience to properly evaluate and permit wind plants. As wind development expands into more complex environments, it is expected that permitting processes and considerations for developers and decision-makers will also increase in complexity.

A list of federal regulatory agencies associated with wind is included in Appendix C.

2.8.3 Conclusions

The U.S. wind industry has grown to an installed capacity of more than 61 GW at the end of 2013. Fifteen states had more than 1 GW of wind in operation in 2014, and all but 11 states had some level of utility-scale wind development. Small (distributed) wind systems have been installed in every state. Offshore wind can open new opportunities for utility-scale wind development, including providing access to high-quality wind resources in some densely populated states that cannot accommodate land-based wind development. This growth demonstrates that siting and permitting processes can be navigated successfully. The creation and implementation of appropriate siting practices and continued research to better understand, minimize, and mitigate the environmental impacts of expanded wind deployment can allow continued development while protecting impacted species and addressing competing use concerns. Achieving penetration levels in the *Wind Vision Study Scenario* will require the continued efforts of the industry, agencies, NGOs, and the general public to extract and apply lessons learned from current and future experiences so the industry can grow efficiently and responsibly.

Section 4.6 of the *Wind Vision* roadmap details the wind siting, permitting, and deployment actions necessary to achieve penetration levels comparable to the *Wind Vision Study Scenario,* including:

- Developing impact reduction and mitigation options for competing human use concerns such as radar, aviation, maritime shipping and navigation;
- Developing strategies to minimize and mitigate siting and environmental impacts of wind power plants, including impacts on wildlife;
- Developing information and strategies to mitigate the local impact of wind deployment and operation by continuing to develop and disseminate accurate information to the public on local impacts of wind power deployment and operations;
- Developing clear and consistent regulatory

guidelines for wind development by streamlining regulatory guidelines for responsible project development on federal, state and private lands, as well as in offshore areas; and

- Developing commonly accepted standard siting and risk assessment tools allowing rapid pre-screening of potential development sites.

2.9 Collaboration, Education, and Outreach

A number of government agencies, industry organizations, researchers, academics, NGOs, and collaborative groups are addressing wind-related issues, from permitting and environmental oversight to manufacturing and workforce training. These parties have also enhanced education to help stakeholders understand the role and impact of wind on the energy market, communities, and the environment.

Collaboration by a wide range of stakeholders has improved understanding of impacts, benefits, and deployment hurdles for wind power, and has increased validity and credibility of related research.

Sections 2.9.1 through 2.9.4 provide a brief overview of the types of organizations involved in wind power, including federal and state agencies, NGOs, regional organizations, academia, and outreach groups. Section 2.9.5 discusses recent collaborative efforts, while Section 2.9.6 provides a summary of recent industry activities. International collaboration efforts are discussed in Section 2.9.7.

2.9.1 Federal

DOE is the primary federal agency engaged in wind power education and outreach, with a focus on providing an exchange for unbiased information about wind deployment and its benefits and impacts. There is increased coordination on wind activities across multiple federal agencies, including the U.S. Department of Commerce, DoD, FAA, the U.S. Geological Service, and DOI (which includes BLM, BOEM, the Bureau of Safety and Environmental Enforcement, USFWS, and the U.S. Geological Service). These federal collaborations are based on expanded interest in supporting the appropriate deployment of wind power technologies.

A Navigant report prepared for DOE in 2013 found 70% of stakeholders in DOE's Stakeholder Outreach and Education (WINDExchange and Wind Powering America) initiatives indicated wind power development would have been lower without federal involvement. The report estimates 3.4 GW of wind power capacity are directly attributable to federal stakeholder outreach and educational programs [58].

2.9.2 State

State-level stakeholder engagement and outreach activities vary, from active programs to support plant development to limited formal activities or even active discouragement of wind development. State-level engagement has generally been limited to states with active wind markets, a strong need to expand wind deployment, or local wind champions. Since the early 2000s, state-level wind outreach efforts have been executed through four primary organizations: respective state energy offices, typically funded through state appropriations or DOE grants; wind-focused trade organizations; state university research or student-led outreach programs; and wind or environmental NGOs including the Wind Working Groups formed through DOE funding. In some states, multiple organizations may work simultaneously. Project developers also undertake outreach activities for specific projects, sometimes in a statewide context.

Educational organizations, including universities and community colleges, are also increasingly active in wind power outreach and stakeholder engagement at the state and community levels. Through activities such as Wind for Schools, AWEA student chapters, active faculty, and other wind or sustainable energy-focused student groups, faculty and students are becoming more involved in public engagement even outside of their research. Faculty at these organizations also typically have knowledge of local wind markets. AWEA and DOE maintain a list of educational organizations active in wind power.

2.9.3 NGO Activities

An increasing number of NGOs advocate for wind power through legislative, regulatory, or market barrier removal efforts. Some support wind power development directly, while others recognize wind power as having a role in achieving other objectives relevant to their organization, such as protecting wildlife, reducing carbon emissions, or promoting local economic development. Types of NGOs engaged in wind power activities include trade organizations, wildlife advocates, clean energy proponents, environmental organizations, organized labor groups, public health organizations, and farmers' organizations. Each NGO brings a unique point of view, level of expertise, and network of influence, which helps enhance overall understanding. The decade prior to 2014 has also seen the initiation of NGOs working to reduce the use of wind power by highlighting potential negative impacts of wind development.

2.9.4 Regional Organizations

As the installed capacity of wind technology increases and wind energy becomes more economically viable, regional organizations from a wide range of stakeholder sectors have embraced expanded appropriate wind energy deployment and are providing valuable support in the ongoing effort to educate decision-makers and other community stakeholders. These regional organizations can be comprised of stakeholders from many sectors, including but not limited to businesses, government agencies (including elected officials), environmental and other non-profit groups, rural and agricultural groups (including landowners), and academic institutions. These organizations work with stakeholders to gather and communicate accurate information about wind power, often to help identify and reduce or mitigate actual and perceived impacts.

Regional organizations exist across the United States, even in regions with limited current deployment of wind power. One example of a new regional organization is the Southeastern Wind Coalition, which works to advance the land-based and offshore wind development by building informational bridges between the wind industry, public, other regional organizations and governmental officials. Regional organizations communicate information through scientific literature, social and earned media, and public events, often with support from federal partners.

2.9.5 Collaborative Efforts

Stakeholders have increasingly employed collaborative efforts to approach some of the most pressing challenges to wind power development. This collaboration pools the resources of industry, conservationists, policy makers, and other interested stakeholders to develop innovative solutions. Work by collaborative groups has shifted from the basic sharing of information and best practices to active engagement aimed at solving specific problems.

Collaborative groups working to resolve issues that can limit wider deployment of wind power include:

- The American Wind Wildlife Institute (*www.awwi.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1);
- The Bats and Wind Energy Cooperative (*www.batsandwind.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1);
- The National Wind Coordinating Collaborative (*www.nationalwind.org*, see *Environmental Impacts of Wind Deployment* in Section 2.8.1), facilitated by AWWI; and
- The Utility Variable-Generation Integration Group (*http://www.uvig.org*, see Section 2.7.5)

2.9.6 Industry Activities

Industry trade associations continue to address siting issues for land-based and distributed wind. As previously discussed, AWEA and DWEA have developed best practices for wind power deployment [231, 77], and the 2011 project development siting guide developed by the Canadian Wind Energy Association demonstrates efforts to ensure successful development of wind through with comprehensive community engagement. These organizations have also done extensive work in stakeholder engagement, outreach, and education at the national, regional, state, and grassroots levels. AWEA and DWEA have standing committees that meet regularly to discuss and address siting challenges. This includes supporting and participating in studies of avian and bat impacts and mitigation approaches, developing sound reduction technology and control algorithms, and working with federal regulators to appropriately deploy wind technologies.

Increasing interest in offshore wind and federal efforts to develop a related permitting process have brought stakeholder concerns to the forefront and expanded industry-focused engagement efforts. Offshore engagement efforts have occurred primarily at the state or local level and have focused on specific projects like Cape Wind. AWEA and several regional organizations are the primary industry organizations addressing offshore wind stakeholder engagement.

2.9.7 International Collaboration

With 28 member countries at the end of 2013,[98] the IEA is the primary organization coordinating international wind-related activities in stakeholder outreach and education. IEA Wind Task 28 was founded in 2010 to consider social acceptance of wind power, and IEA Wind Task 34 started in 2014 to help expand international collaboration on the environmental impacts of land and offshore based wind systems. This international exchange on acceptance issues has proven valuable for those engaged in the work, as well as for government administrators, the research community, IEA Wind members, and wind industry in the respective countries. Other international informational projects are conducted by many European nations and the European Union. The International Renewable Energy Agency, a consortium of more than 130 countries, has initiated efforts to expand the acceptance of all renewable energy technologies, including wind. The Global Wind Energy Council also acts internationally, to consolidate and communicate industry viewpoints, provide information on the benefits and impacts of wind, conduct authoritative research and policy analysis, and support wider international dialogue about appropriate wind deployment.

2.9.8 Conclusions

Collaboration by a wide range of stakeholders has improved understanding of the impacts, benefits, and deployment hurdles for wind power, and has increased validity and credibility of related research. Continued collaboration, education, and outreach will be required to achieve the deployment levels in the *Wind Vision Study Scenario*. Section 4.7 of the *Wind Vision* roadmap details important collaboration, education, and outreach actions related to these efforts. These actions include providing information on wind power impacts and benefits and increasing public understanding of broader societal impacts of wind power, including economic impacts, reduced emissions of GHGs and air pollutants, less water use, and greater energy diversity. Additional actions include fostering international exchange and collaboration on technology research and development; standards and certifications; and best practices in siting, operations, repowering, and decommissioning.

98. *www.iea.org/countries/membercountries/*

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3 Impacts of the *Wind Vision*

Summary

Chapter 3 of the *Wind Vision* identifies and quantifies an array of impacts associated with continued deployment of wind energy. This chapter provides a detailed accounting of the methods applied and results from this work. Costs, benefits, and other impacts are assessed for a future scenario that is consistent with economic modeling outcomes detailed in Chapter 1 of the *Wind Vision*, as well as existing industry construction and manufacturing capacity, and past research. Impacts reported here are intended to facilitate informed discussions of the broad-based value of wind energy as part of the nation's electricity future.

The primary tool used to evaluate impacts is the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) model. ReEDS is a capacity expansion model that simulates the construction and operation of generation and transmission capacity to meet electricity demand. In addition to the ReEDS model, other methods are applied to analyze and quantify additional impacts.

Modeling analysis is focused on the *Wind Vision Study Scenario* (referred to as the *Study Scenario)* and the *Baseline Scenario*. The *Study Scenario* is defined as wind penetration, as a share of annual end-use electricity demand, of 10% by 2020, 20% by 2030, and 35% by 2050. In contrast, the *Baseline Scenario* holds the installed capacity of wind constant at levels observed through year-end 2013. In doing so, the *Baseline Scenario* provides the requisite point of comparison from which the incremental impact of all future wind deployment and generation can be assessed. Sensitivity analyses around the *Study Scenario*—varying wind technology cost and performance and fossil fuel costs while holding the wind penetration trajectory at the 10%, 20%, 35% levels—are used to assess the robustness of key results and highlight the impacts of changes in these variables. Sensitivities include single variable *Low/High Wind Cost* or *Low/High Fossil Fuel Cost Scenarios,* as well as combined *Unfavorable* (High Wind Cost and Low Fossil Fuel Cost) and *Favorable* (Low Wind Cost and High Fossil Fuel Cost) *Scenarios.*

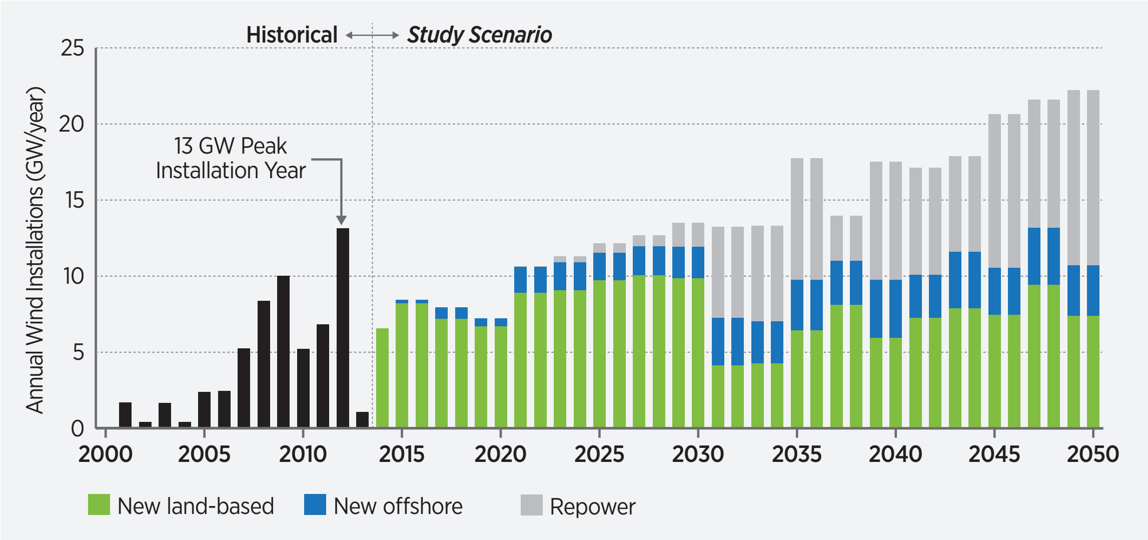
Many of the results presented in this chapter emphasize outcomes across the full range of sensitivities. In some instances, however, results are presented only for a single central case. This central case, referred to as the *Central Study Scenario,* applies common modeling inputs with the *Business-as-Usual (BAU) Scenario* but also includes the prescribed wind trajectory of 10% by 2020, 20% by 2030, 35% by 2050. Where the *Central Study Scenario* is the point of focus (e.g., greenhouse gas reductions, air pollution reductions), uncertainty is typically reflected by a range in the value of a given impact. For several additional impacts analyzed, results are discussed qualitatively (e.g., wildlife, offshore and distributed wind) or reported in absolute terms for the *Study Scenario* rather than relative to the *Baseline Scenario* (e.g., cumulative installed wind capacity, land area impacts, and gross jobs supported by wind investments).

Within the *Wind Vision* analysis, existing policies are represented and analyzed as of January 1, 2014 (e.g., the wind production tax credit [PTC] is expired). No new policies beyond these existing policies, including new or proposed environmental regulations, are explicitly modeled.

Impacts, costs, and benefits of the scenarios presented here are contingent on the analysis approach of prescribed wind penetration levels in the electric sector. Because the resulting impacts, costs, and benefits depend, in part, on underlying policy and market conditions as well as economy-wide interactions, alternative approaches to reaching the wind penetration levels outlined here would yield different results.

Wind Industry and Electric Sector Impacts in the Study Scenario

In the *Central Study Scenario*, total installed wind capacity increases from the 61 gigawatts (GW) installed by year-end 2013 to approximately 113 GW by 2020, 224 GW by 2030, and 404 GW by 2050. This growth represents nearly three doublings of installed capacity and includes all wind applications: land-based, distributed, and offshore wind. Of these installed capacity amounts, offshore wind comprises 3 GW, 22 GW, and 86 GW for 2020, 2030, and 2050, respectively. The amount of installed capacity needed to meet the deployment levels considered in the *Study Scenario* will depend on future wind technology development. For example, with improvements in wind technology yielding higher capacity factors, only 382 GW of wind capacity are needed to reach the 35% penetration level in 2050. Conversely, 459 GW would be required using 2013 technologies with only limited advancements. Across the full range of technology assumptions, the *Study Scenario* utilizes only a fraction of the more than 10,000 GW of gross wind resource potential.



Note: New capacity installations include capacity added at a new location to increase the total cumulative installed capacity or to replace retiring capacity elsewhere. Repowered capacity reflects turbine replacements occurring after plants reach their useful lifetime. Wind installations shown here are based on model outcomes for the *Central Study Scenario* and do not represent projected demand for wind capacity. Levels of wind capacity to achieve the penetration trajectory in the *Study Scenario* will be affected by future advancements in wind turbine technology, the quality of the wind resource where projects are located, and market conditions, among other factors.

Figure 3-1. Historical and forward-looking wind power capacity in the *Central Study Scenario*

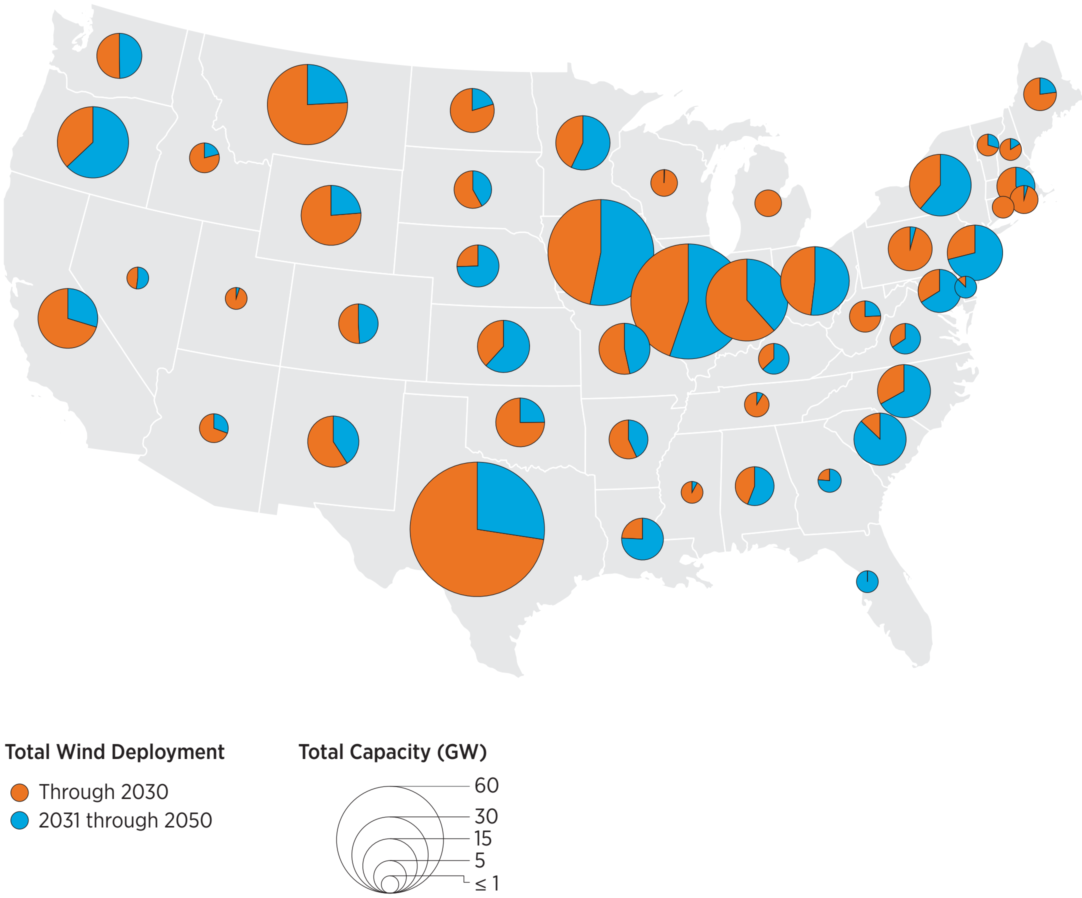
The *Study Scenario* supports new capacity additions at levels comparable to the past, but drives increased demand for new wind turbine equipment as a function of repowering needs. Demand for wind turbines averages approximately 8 GW/year from 2014 to 2020, 12 GW/year from 2021 to 2030, and increases to 18 GW/year from 2031 to 2050. While aggregate demand trends upward (Figure 3-1), it is primarily concentrated in new land-based wind in the near term. Deployment of offshore plants and repowering (the replacement of turbine equipment at the end of its useful life with new state-of-the-art turbine equipment) become more substantive factors in the 2031–2050 timeframe.

In the *Study Scenario,* wind industry expenditures (new capital and development expenditures, annual operating expenditures, and repowered capital expenditures) grow to more than $30 billion/year (in constant 2013 dollars) from 2020 to 2030, and are estimated at approximately $70 billion/year by 2050.[1] By 2050, annual expenditures exceed $23 billion/year for operations, $22 billion/year for repowering, and $25 billion/year for new greenfield development.

The *Study Scenario* suggests continued geographical diversity in wind power deployment. Figure 3-2 illustrates the state-level distribution of wind capacity (land-based and offshore) in 2030 and 2050 under the *Central Study Scenario*. By 2030, installed wind capacity exists in all but one state, with 37 states having more than 1 GW of capacity. By 2050, wind capacity exists in all 50 states, with 40 states having more than 1 GW of installed wind capacity.[2]

Variations in wind resource quality, relative distances to load centers, and existing infrastructure drive regional differences in modeled wind penetration levels. Based on model outcomes from the *Study Scenario*, most of the western and central parts of the United States have penetration levels that exceed the 10% nationwide level by 2020, with some regions approaching or exceeding 30% penetration. By 2050, wind penetration levels exceed 40% across much of the West and upper Midwest, with levels of 10%–40% in California, the mid-Atlantic, and New England. In the Southeast, wind penetration

1. Unless otherwise specified, all financial results reported in this chapter are in 2013$.
2. As of 2013, wind installations of 62 MW and 206 MW exist in Alaska and Hawaii respectively. While future wind deployment in these states is expected and could potentially grow beyond 1 GW, these states are not counted among the states with more than 1 GW in 2030 or 2050 because the modeling analysis was restricted to the 48 contiguous United States.



Note: Results presented are for the *Central Study Scenario.* Across *Study Scenario* sensitivites, deployment by state may vary depending on changes in wind technology, regional fossil fuel prices, and other factors. ReEDS model decision-making reflects a national optimization perspective. Actual distribution of wind capacity will be affected by local, regional, and other factors not fully represented here. Alaska and Hawaii already had wind deployment in 2013. However, future deployment estimates are limited to the 48 contiguous United States due to modeling scope.

Figure 3-2. *Study Scenario* distribution of wind capacity by state in 2030 and 2050

levels by 2050 are lower than in other regions and range from less than 1% (Florida) to more than 20% (coastal Carolinas).

The levels of wind penetration examined in the *Study Scenario* increase variability and uncertainty in electric power system planning and operations (Figure 3-3). From the perspective of planning reserves, the aggregated capacity value of wind power in the *Study Scenario* is about 10–15% in 2050 (with lower marginal capacity value). This reduces the ability of wind compared to other electricity generation to contribute to increases in peak planning reserve requirements. In addition, the uncertainty introduced by wind in the *Study Scenario* increases the level of operating reserves that must be maintained by the system. Operational constraints result in average curtailment of 2–3% of wind generation starting around 2030, modestly increasing the threshold for economic wind deployment. These costs are embedded in the system costs and retail rate impacts noted. Such challenges can be mitigated by various means, including increased system flexibility, greater electric system coordination, faster dispatch schedules, improved forecasting, demand response, greater power plant cycling, and—in some cases—storage options. Specific circumstances dictate the best solution. Continued research is expected to provide more specific and localized assessments of impacts, as further discussed in Chapter 4.

Industry Investment	Deployment	Integration[b]	Transmission[c]	Offshore Wind
• 8–11 GW/year average net capacity additions throughout the 2013–2050 period • 18 GW/year annual turbine demand as more wind plants are repowered from 2031 to 2050 • $70 billion/year[a] by 2050 annual wind industry investment from new capacity additions, repowered capacity, and operations and maintenance	• 404 GW of cumulative capacity by 2050 for 35% wind energy • All 50 states with wind deployment by 2050 • 37 states by 2030 and 40 by 2050 with more than 1 GW of wind power (within the contiguous United States)	• Increased system flexibility is required, but can be acquired from many sources • 2–3% average curtailment of annual wind generation; estimated wind capacity value of 10–15% by 2050 • Integration solutions required, but will vary by region	• 2.7x incremental transmission needs by 2030; 4.2x by 2050 • 10 million MW-miles incremental transmission capacity required by 2030 Cumulatively 29 million incremental MW-miles required by 2050 • Through 2020: incremental 350 circuit miles/year needed 2021–2030: incremental 890 circuit miles/year, and 2031–2050: incremental 1,050 circuit miles/year	• Established U.S. offshore wind market and supply chain by 2020 • 22 GW installed by 2030 and 86 GW installed by 2050 • By 2050, offshore wind in multiple regions, including the East Coast, West Coast, Great Lakes, and Gulf of Mexico

a. Expenditures in 2013$

b. Increased costs associated with greater demand for system flexibility and wind curtailments are embedded in the system costs and retail rate impacts reported in Chapter 3.

c. All transmission estimates reported are the incremental difference between the *Study Scenario* and *Baseline Scenario*. Estimated circuit miles assume a single-circuit 345-kilovolt transmission line with a nominal carrying capacity of 900 MW. ReEDS transmission capacity additions exclude those added for reliability purposes only and conductor replacement on existing infrastructure. Estimates shown here represent point to point transfers, for which explicit corridors have not been identified.

Figure 3-3. Summary of wind industry and other electric sector impacts in the *Central Study Scenario*

Transmission expansion is another key variable with respect to future wind deployment. New transmission capacity to support the *Study Scenario* is 2.7 times greater in 2030 than the respective *Baseline Scenario,* and about 4.2 times greater in 2050 (Table 3-1). Although transmission expansion needs are greater in the *Study Scenario,* transmission expenditures are less than 2% of total electric sector costs. Incremental cumulative (beginning in 2013) transmission needs of the *Central Study Scenario* relative to the *Baseline Scenario* amount to 10 million megawatt (MW)-miles by 2030 and 29 million MW-miles by 2050. Assuming single-circuit 345-kilovolt (kV) lines (with a 900-MW carrying capacity) are used to accomplish this increase, an average of 890 circuit miles/year of new transmission lines would be needed between 2021 and 2030, and 1,050 circuit miles/year between 2031 and 2050 (Table 3-1). This compares with the recent (as of 2013) average of 870 circuit miles added each year since 1991.[3]

In the *Study Scenario*, wind primarily displaces fossil fuel-fired generation, especially natural gas, with the amount of displaced gas growing over time (Figure 3-4). In the long-term (after 2030), wind in the *Study Scenario* also affects the growth of other renewable generation and, potentially, future growth

3. Transmission estimates for the *Study Scenario* exclude maintenance for the existing grid, reliability-driven transmission, and other factors that would be similar between the *Baseline Scenario* and *Study Scenario.*

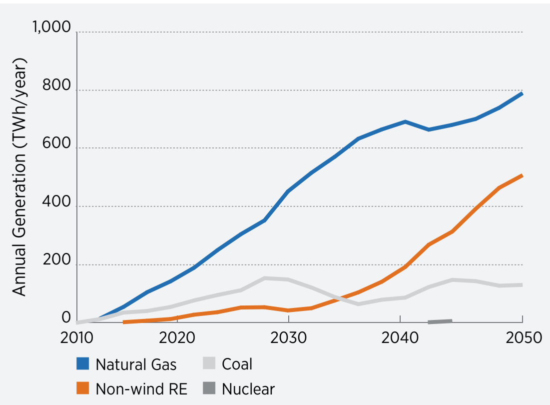
Table 3-1. Transmission Impacts in the *Central Study Scenario*

	Historical Average	2014–2020	2021–2030	2031–2050	Cumulative 2014–2050
Study Scenario MW-miles (change from *Baseline Scenario*)		311,000/year	801,000/year	949,000/year	29,000,000
Study Scenario circuit miles (change from *Baseline Scenario*)[a]	870/year	350/year	890/year	1,050/year	33,000
		By 2020	**By 2030**	**By 2050**	
Ratio of *Study Scenario* to *Baseline Scenario*		1.5x	2.7x	4.2x	

Note: ReEDS transmission capacity additions exclude those added for reliability purposes only and conductor replacement on existing infrastructure. Estimates shown here represent point to point transfers, for which explicit corridors have not been identified.

a. Assuming a representative transmission line with a carrying capacity of 900 MW, typical for single-circuit 345-kV lines

of nuclear generation. The avoided generation mix will ultimately depend on uncertain future market conditions, including fossil fuel prices and technology costs. Displaced fossil fuel consumption leads to avoided emissions and other social impacts. With wind penetration increasing to the levels envisioned under the *Study Scenario*, the role of the fossil fleet in providing energy declines, while its role to provide reserves increases.



Note: The positive values indicate there was greater generation from these sources under the *Baseline Scenario* compared with the *Study Scenario*. The "natural gas" category includes oil-fired generation. Non-wind RE refers to non-wind renewable energy.

Figure 3-4. Change in annual generation between the *Central Baseline Scenario* and the *Central Study Scenario* by technology type

Costs of the *Wind Vision Study Scenario*

National average retail electricity prices for both the *Baseline Scenario* and the *Study Scenario* are estimated to grow (in real terms) between 2013 and 2050. Through 2030, incremental retail electricity prices of the *Central Study Scenario* are less than 1% higher than those of the *Baseline Scenario*. In the long-term (2050), retail electricity prices are expected to be lower by 2% in the *Central Study Scenario* relative to the *Baseline Scenario*.

A wider range of future costs and savings are possible as estimated by the sensitivity scenarios. Sensitivities analyzed include specific scenarios in which wind costs or fossil fuel costs are expected to be higher and lower than those estimated in the *Central Study Scenario*. Sensitivities analyzed also include scenarios where both wind costs and fossil fuel costs are altered such that low wind costs are coupled with high fossil fuel prices and high wind costs are coupled with low fossil fuel prices.

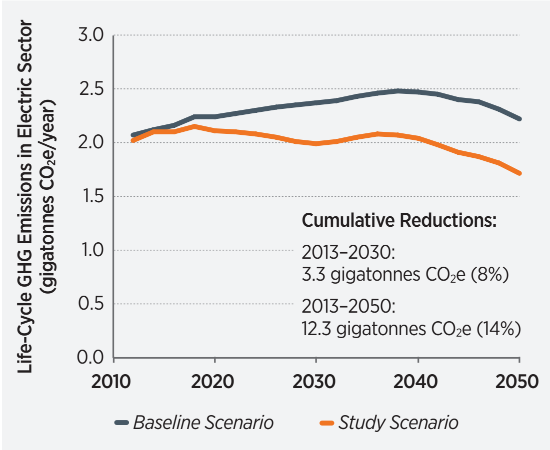
In 2020, the range of estimated incremental retail electricity rate ranges from a nearly zero cost difference vs. the *Baseline Scenario* up to a 1% cost increase. In 2030, incremental costs are estimated to be as high as a 3% increase vs. the *Baseline Scenario* under the most unfavorable conditions for wind (low fuel cost combined with high wind power costs). Under the most favorable conditions modeled (high fuel cost combined with low wind costs), the *Study Scenario* results in a 2% reduction in retail electricity prices relative to the *Baseline Scenario*. By 2050, incremental electricity prices of all cases of the *Study Scenario* are estimated to range from a 5% increase to a 5% savings over the corresponding *Baseline Scenario*.

On an *annual* basis for the *Central Study Scenario*, consumers of electricity incur an increase in costs of $2.3 billion (0.06¢ per kilowatt-hour [kWh]) in 2020 and $1.5 billion (0.03¢ per kWh) in 2030, but realize a savings of $14 billion (0.28¢/kWh) in 2050, as compared to the *Baseline Scenario*. Across the range of sensitivities, annual impacts to consumers range from the potential for costs as well as savings. In the near-term (2020), cost increases of $0.8–$3.6 billion are observed. In the mid-term (2030), consumer electricity cost effects range from savings of up to $12 billion to costs of up to $15 billion. In the long-term (2050), consumer electricity cost effects range from savings of up to $31 billion or costs of up to $27 billion. Electricity costs and savings from future wind deployment will depend strongly on future technology and fossil fuel cost conditions, with low technology costs or high fossil fuel costs supporting savings and stagnant technology or relatively lower fossil fuel costs driving consumer costs.

In present value terms, cumulative electric sector expenditures (fuel, capital, operating, and transmission) are lower for the *Study Scenario* than for the *Baseline Scenario* across most sensitivities evaluated. From 2013 to 2050, the *Central Study Scenario* results in cumulative present value (using a 3% real discount rate) savings of approximately $149 billion (-3%). Potential electricity sector expenditures range from savings of $388 billion (-7%) to a cost increase of $254 billion (+6%), depending on future wind technology cost trends and fossil fuel costs.

Societal Benefits of the *Wind Vision Study Scenario*

The *Central Study Scenario* reduces electric sector life-cycle greenhouse gas (GHG) emissions by 6% in 2020 (0.13 gigatonnes of carbon dioxide equivalents, or CO_2e), 16% in 2030 (0.38 gigatonnes CO_2e), and 23% in 2050 (0.51 gigatonnes CO_2e), compared to the *Baseline Scenario*. Cumulative GHG emissions are



Note: Life-cycle GHG emissions include upstream emissions, ongoing combustion and non-combustion emissions, and downstream emissions. Upstream and downstream emissions include emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, on-site construction, project decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the equipment and other site material.

Figure 3-5. Life-cycle GHG emissions in the *Central Study Scenario* and *Baseline Scenario*

Table 3-2. Example Economic and Health Benefits from Reduced Air Pollution in the *Central Study Scenario* Relative to the *Baseline Scenario*

Type of Benefit	Amounts
Cumulative monetized benefits (2013$)	$108 billion
Avoided premature deaths	21,700
Avoided emergency room visits for asthma due to $PM_{2.5}$ effects	10,100
Avoided school loss days due to ozone effects	2,459,600

Note: Central estimate results are presented, which follow the 'EPA Low' methodology for calculating benefits, further detailed in Section 3.8. Monetized benefits are discounted at 3%, but mortality and morbidity values are simply accumulated over the 2013–2050 time period. Health impacts presented here are a subset of those analyzed and detailed in Section 3.8.

reduced by 12.3 gigatonnes CO_2e from 2013 to 2050 (14%) (Figure 3-5). Based on the U.S. Interagency Working Group's (IWG's) Social Cost of Carbon (SCC) estimates, these reductions yield global avoided climate change damages of an estimated $85–$1,230 billion, with a central estimate of $400 billion (2013–2050 discounted present value). This is equivalent to a levelized benefit of wind energy ranging from 0.7¢ per kWh of wind to 10¢ per kWh of wind, with a central levelized benefit estimate of 3.2¢ per kWh of wind.

The *Central Study Scenario*, as compared with the *Baseline Scenario*, results in reductions in other air pollutants including fine particulate matter, sulfur dioxide, and nitrogen oxides ($PM_{2.5}$, SO_2, and NO_X). These reductions yield societal health and environmental benefits that range from $52–$272 billion (2013–2050, discounted present values) depending on the methods of quantification. The single largest driver of these benefits is reduced premature mortality resulting from reductions in SO_2 emissions in the eastern United States. In total, the air pollution impacts of the *Study Scenario* are equivalent to a levelized benefit of wind energy that ranges from 0.4¢ per kWh of wind to 2.2¢ per kWh of wind. A selection of health outcomes is listed in Table 3-2.

The *Central Study Scenario* results in reductions in national electric-sector water withdrawals (1% reduction in 2020, 4% in 2030, and 15% in 2050) and water consumption (4% reduction in 2020, 11% in 2030, and 23% in 2050), compared to the *Baseline Scenario.*[4] Anticipated reductions, relative to the *Baseline Scenario*, exist in many parts of the United States, including the water-stressed arid states in the Southwest (Figure 3-6). Water use reductions driven by the *Study Scenario* offer environmental and economic benefits as well as reduced competition for scarce water resources.

The total value of reduced GHG and air pollution emissions in the *Central Study Scenario* relative to the *Baseline Scenario* exceeds the estimated increase in electricity rates observed in the 2020 and 2030 time periods by three and 20 times, respectively. By 2050, the *Central Study Scenario* results in savings across all three categories—electricity rates ($14 billion), GHG emissions ($42 billion), and air pollution emissions ($10 billion) (Figure 3-7). On a cumulative basis, savings across these metrics are also experienced for the *Central Study Scenario* relative to the *Baseline Scenario* (Figure 3-8). These quantitative outcomes hold across many of the sensitivities analyzed.

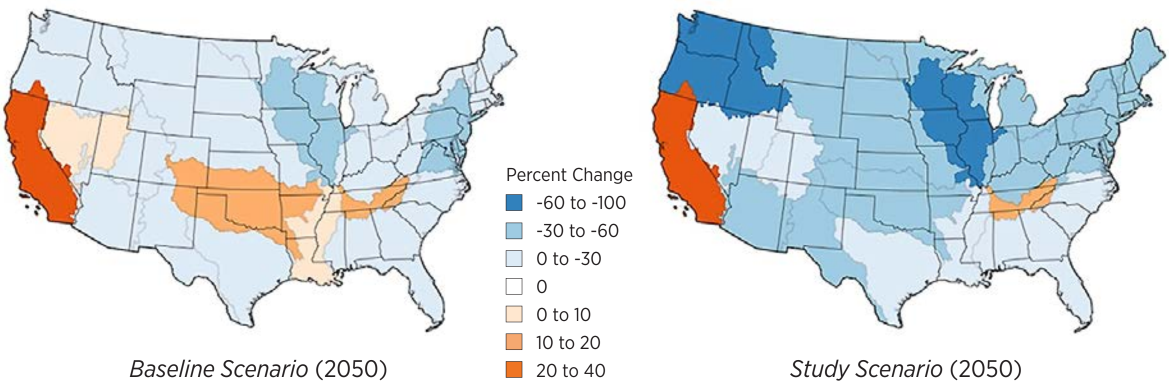
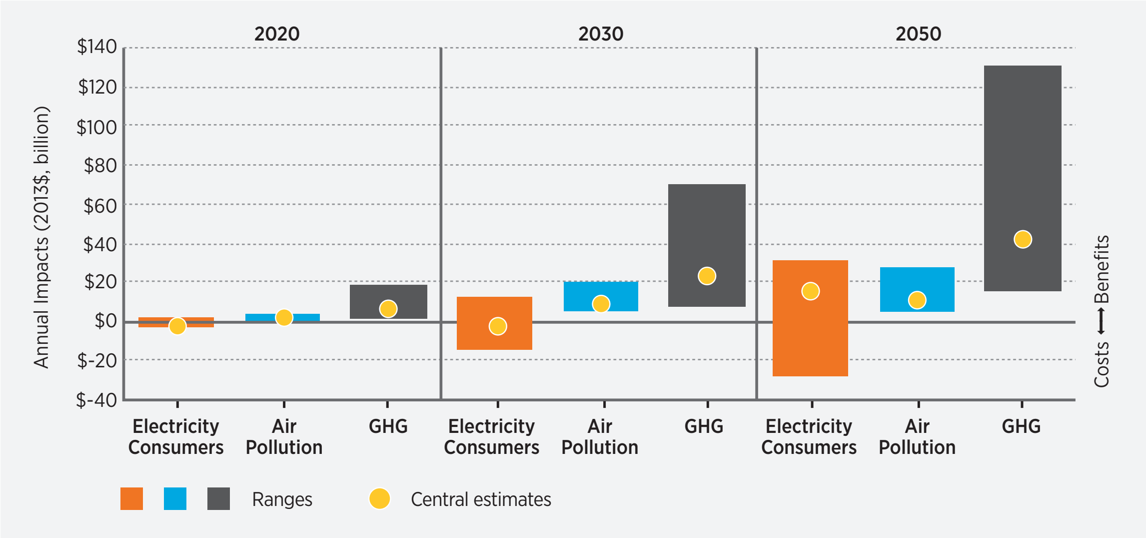


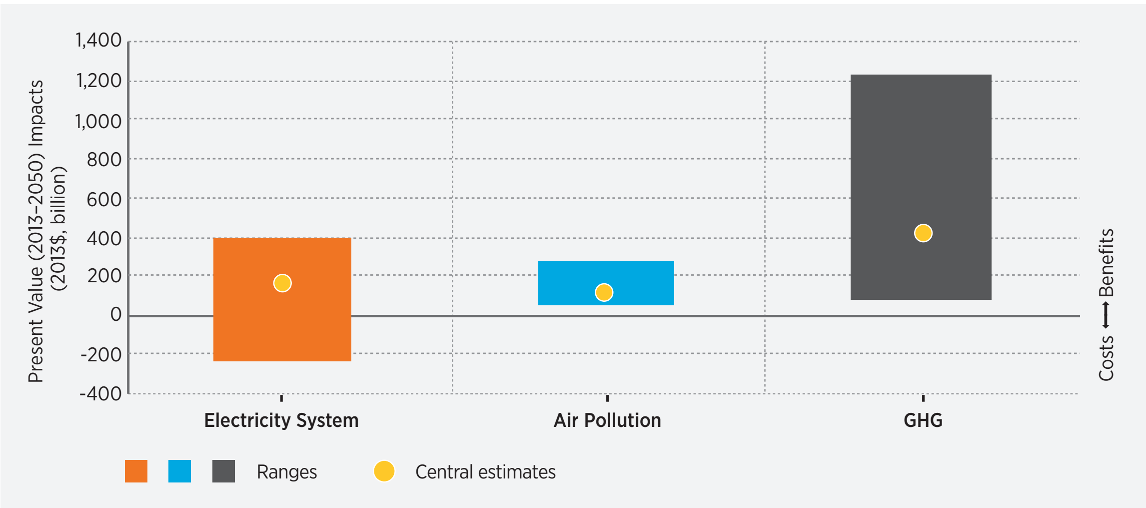
Figure 3-6. Change in water consumption used in electricity generation from 2013 to 2050 for the *Baseline Scenario* and *Central Study Scenario*

4. Water withdrawal is defined as water removed from the ground or diverted from a water source for use, but then returned to the source, often at a higher temperature. Water consumption is defined as water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment.



Note: Results represent the annual incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario.* Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity consumers costs range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

Figure 3-7. Monetized impacts of the *Study Scenario* relative to the *Baseline Scenario* in 2020, 2030, and 2050



Note: Results represent the present value of incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario.* Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity system cost range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

Figure 3-8. Cumulative (2013–2050) present value of monetized impacts of the *Study Scenario* relative to the *Baseline Scenario*

Additional Impacts Associated with the Study Scenario

The *Study Scenario* contributes to reductions in both long-term natural gas price risk and natural gas prices, compared to the *Baseline Scenario.*[5] The *Central Study Scenario* results in total electric system costs that are 20% less sensitive to long-term fluctuations in coal and natural gas prices. Additionally, the *Study Scenario* leads to a potential $280 billion in consumer savings due to reduced natural gas prices outside the electric sector, equivalent to a levelized consumer benefit from wind energy of 2.3¢ per kWh of wind.

The *Study Scenario* supports a robust domestic wind industry, with wind-related gross jobs from investments in new and operating wind power plants ranging from 201,000 to 265,000 in 2030, and increasing to between 526,000 and 670,000 in 2050. Actual future wind-related jobs (on-site, supply chain, and induced) will depend on the future strength of the domestic supply chain and additional training and educational programs as necessary.

Wind project development examined in the *Wind Vision* affects local communities through land lease payments and local property taxes. Under the *Central Study Scenario*, wind power capacity additions lead to land-based lease payments that increase from $350 million in 2020 to $650 million in 2030, and then to $1,020 million in 2050. Offshore wind lease payments increase from $15 million in 2020 to $110 million in 2030, and then to $440 million in 2050. Property tax payments associated with wind projects are estimated to be $900 million in 2020; $1,770 million in 2030; and $3,200 million in 2050.

Under the *Study Scenario,* the land area occupied by turbines, roads, and other infrastructure for wind development equates to 0.03% of the land area in the contiguous United States in 2030 and 0.04% in 2050. For comparison, this area equates to less than one-third of land area occupied by U.S. golf courses in 2013. Land area occupied by wind power plants (accounting for requisite turbine spacing and typical densities) equates to less than 1.5% of the land area in the contiguous United States by 2050. Land surrounding wind power plants is typically able to support other land uses, such as ranching and farming.

Continued wind deployment will need to be executed with sensitivity to the potential impacts on avian, bat, and other wildlife populations; the local environment; the landscape; and communities and individuals living in proximity to wind projects. Experience, continued research, and technological solutions (e.g., strategic operational strategies and wildlife deterrents) are expected to make siting and mitigation more effective and efficient.

5. Wind power can be sold at fixed prices for long periods (e.g., 20 years), and, as a result, provides a hedge against volatility in commodity fuels such as natural gas. When wind power is a more significant part of the electricity generation portfolio, as is the case in the *Study Scenario*, electricity system costs are less sensitive to market fluctuations in fossil fuel prices. In addition, deployment and operation of wind power plants reduces demand for fossil fuels, including natural gas, leading to lower fuel prices within and outside of the electric sector and supporting cost savings for consumers.

System Costs[a]	Benefits[a,b,c]		
	GHG	Air Pollution	H_2O
$149 billion (3%) lower cumulative electric sector expenditures	14% reduction in cumulative GHG emissions (12.3 gigatonnes CO_2-equivalents), saving $400 billion in avoided global damages	$108 billion savings in avoided mortality, morbidity, and economic damages from cumulative reductions in emissions of SO_2, NO_x, and PM 21,700 premature deaths from air pollution avoided	23% less water consumption and 15% less water withdrawals for the electric power sector

Additional Impacts

Energy Diversity	Jobs	Local Revenues	Land Use	Public Acceptance and Wildlife
Increased wind power adds fuel diversity, making the overall electric sector 20% less sensitive to changes in fossil fuel costs. The predictable, long-term costs of wind power create downward price pressure on fossil fuels that can cumulatively save consumers $280 billion from lower natural gas prices outside the electric sector.	Approximately 600,000 wind-related gross jobs spread across the nation.	$1 billion in annual land lease payments $440 million annual lease payments for offshore wind plants More than $3 billion in annual property tax payments	Less than 1.5% (106,000 km^2) of contiguous U.S. land area occupied by wind power plants Less than 0.04% (3,300 km^2) of contiguous U.S. land area impacted by turbine pads, roads, and other associated infrastructure	Careful siting, continued research, thoughtful public engagement, and an emphasis on optimizing coexistence can support continued responsible deployment that minimizes or eliminates negative impacts to wildlife and local communities.

Note: Cumulative costs and benefits are reported on a Net Present Value basis for the period of 2013 through 2050 and reflect the difference in impacts between the *Central Study Scenario* and the *Baseline Scenario*. Results reported here reflect central estimates within a range.

a. Electric sector expenditures include capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled, but excludes consideration of estimated benefits (e.g., GHG emissions).

b. Morbidity is the incidence of disease or rate of sickness in a population.

c. Water consumption refers to water that is used and not returned to the source. Water withdrawals are eventually returned to the water source.

Figure 3-9. Summary of costs, benefits, and other outcomes associated with the *Central Study Scenario* relative to the *Baseline Scenario* by 2050

Benefits Specific to Offshore and Distributed Wind

Contributions from offshore wind under the *Study Scenario* are characterized by an industrial base that evolves from its nascent state in 2013 to one that can supply more than 20 GW of offshore capacity by 2030 and more than 80 GW by 2050. This deployment represents just 5.5% of the resource potential for offshore areas adjacent to the 28 coastal and Great Lakes states. Under this scenario, the offshore wind industry would complement and bolster a strong land-based industry through the use of common supply chain components and the development of workforce synergies.

The cost of offshore wind needs to be reduced. Through innovation and increasing scale, however, this market segment could bring notable potential benefits. In particular, offshore wind offers the ability to reduce wholesale market power clearing prices and consumer costs in transmission-congested coastal areas, supports local jobs and port development opportunities, and offers geographic proximity to densely populated coastal regions with limited renewable power alternatives.

Distributed wind applications, including customer-sited wind and wind turbines embedded in distribution networks, offer a number of unique attributes relevant to the *Wind Vision*. On-site distributed wind turbines allow farmers, schools, and other energy users to benefit from reduced utility bills, predictable costs, and a hedge against the possibility of rising retail electricity rates. At the same time, decentralized generation such as distributed wind can benefit the electrical grid. Distributed wind also supports a domestic market; U.S. suppliers dominate the domestic small wind turbine market, with 93% of 2013 sales on a unit basis and 88% on a capacity basis. These suppliers maintain domestic content levels of 80–85% for turbine and tower hardware and are well positioned to capitalize on export opportunities, including growing global demand for decentralized electricity.

Conclusion

Wind power has the potential to provide a substantial share of the nation's electricity at modest near- and mid-term costs and with long-term savings. Overcoming these costs and achieving the *Study Scenario* would require an array of actions (detailed in Chapter 4), but analysis also suggests that robust deployment of wind offers the opportunity to realize a range of additional benefits. Based on current estimates, these benefits exceed the expected near- and mid-term investments and other costs that might result from continued growth of wind energy, across nearly all analyzed scenarios.

3.0 Introduction

Wind industry proponents often point to societal attributes such as lower GHG emissions and rural economic development opportunities as a basis for deployment of wind power. Critics argue that the costs associated with deployment and operation of wind power offset the potential benefits. This chapter informs both perspectives by providing a detailed accounting of various impacts associated with wind deployment under the *Wind Vision Study Scenario*. While Chapter 2 is a retrospective analysis, Chapter 3 provides an assessment of potential future impacts.

Reported impacts are assessed across a number of societal variables. Where possible, impacts are quantified and reported as costs and benefits. Changes in electricity rates, annual electricity consumer costs or savings, and cumulative system expenditures are quantified and reported based on a range of future fossil fuel prices and cost trajectories for wind technology. Impacts on GHG emissions, human health and the environment, water consumption and withdrawals, energy diversity and risk reduction, wind workforce and economic development, transmission and other infrastructure needs, and land use are also analyzed and reported quantitatively. Issues related to electric system reliability, operations and markets, and public acceptance and local impacts are also considered and discussed.

The *Wind Vision* impacts assessment relies on scenarios of future wind deployment to estimate incremental impacts. As discussed in Chapter 1, the *Study Scenario* uses prescribed wind energy penetration levels of 10% by 2020, 20% by 2030, and 35% by 2050, a portion of which is assumed to be offshore wind.[6,7] These penetration levels are grounded in a broad analysis of wind deployment under various market and technology conditions, recent industry trends, and wind energy penetration levels studied in prior work [1, 2]. Impacts from the *Study Scenario* are compared with the *Baseline Scenario*, which holds wind capacity constant at year-end 2013 levels. This approach allows for the quantification of impacts from all future wind deployment. More comprehensive discussion of the development of the *Study Scenario* and the *Baseline Scenario* is in Chapter 1.

In addition to detailing the impacts assessment and general quantification of costs and benefits, this chapter discusses the electric sector modeling methods and relevant modeling inputs. These aspects are covered in Sections 3.1 and 3.2, respectively. Using these tools, Section 3.3 translates the *Study Scenario* into more concrete implications for the wind industry in terms of annual capacity additions and investment. Section 3.4 details the expected impacts on electricity rates and system costs. Sections 3.5 and 3.6 highlight the expected changes in the national generation mix under the *Study Scenario* and the relevant impacts to the electric system. Each of these sections is based on a comparison of the *Study Scenario* with the *Baseline Scenario*. Given uncertainties about future wind energy costs as well as the cost of fossil generation, sensitivities are also considered in order to provide further insight.

Sections 3.7–3.12 describe various additional benefits and impacts of the *Study Scenario*:

- Greenhouse Gas Emissions Reductions (Section 3.7)
- Air Pollution Impacts (Section 3.8)
- Water Usage Reduction (Section 3.9)
- Energy Diversity and Risk Reduction (Section 3.10)
- Workforce and Economic and Development Impacts (Section 3.11)
- Local Impacts, including land area (Section 3.12)

In these sections, the core electric sector modeling results are supplemented with additional analysis tools and assumptions to quantify impacts. The focus is principally on a comparison of the *Study Scenario* under central conditions (i.e., the *Central Study Scenario*) with the respective *Baseline Scenario*

6. Percentage wind energy penetration is calculated as the share of total wind generation relative to total end-use energy demand.

7. Distributed wind turbines connected to the transmission grid are represented within the larger land-based designation. Turbines sited to serve onsite customer needs (connected to the distribution grid) are not captured in the *Wind Vision* report or its quantitative analysis due to limited modeling capabilities. These modeling capabilities are under development and a vision report specific to distributed wind is planned for 2015. Unique benefits of distributed wind are discussed in greater detail in Section 3.13.2.

(i.e., the reference scenario with the corresponding central fuel price assumption). A range of results is often presented and is based on other considerations (apart from the fossil fuel prices and wind cost assumptions that are the basis of the sensitivities in Sections 3.3–3.6).

Finally, Section 3.13 discusses unique benefits associated with offshore and distributed wind that are not otherwise covered in depth in other sections of the chapter. Various appendices provide further details on the methods applied in this chapter and are noted where applicable.

3.1 Impacts Assessment Methods and Scenarios

The economic, environmental, and social impacts of wind deployment depend on the evolution of wind technology and the context under which the deployment occurs. For example, the relative economics of wind will depend on wind technology improvements as well as technology improvements of other power generation technologies and the associated fuel costs. The environmental or social benefits of wind power are also dependent upon the quantity and type of generation displaced. While the market conditions for wind deployment will evolve and there is increasing uncertainty further into the future, impacts assessment over the near- (2020), mid- (2030), and long- (2050) term facilitates understanding of the potential range of costs and benefits of greater wind deployment.

Estimating these future impacts requires analysis techniques that capture the potential evolution of wind technologies as well as potential changes within the power sector given current trends and expectations. The following section describes the computational tools used for this analysis and introduces the scenarios designed to estimate the future impact of the *Study Scenario*.

3.1.1 Regional Energy Deployment System (ReEDS) Model

The primary analytic tool used for the *Wind Vision* impacts assessment is NREL's ReEDS electric sector capacity expansion model [3]. ReEDS simulates the construction and operation of generation and transmission capacity to meet electricity demand. The model relies on system-wide least cost optimization to estimate the type and location of fossil, nuclear, renewable, and storage resource development; the transmission infrastructure expansion requirements of those installations; and the generator dispatch and fuel needed to satisfy regional demand requirements and maintain grid system adequacy. The model also considers technology, resource, and policy constraints, including state renewable portfolio standards. ReEDS models scenarios of the continental U.S. electricity system in two-year solve periods out to 2050.[8] Within the context of the *Wind Vision*, ReEDS is used to generate a set of future scenarios of the U.S. electricity sector from which the impacts of a high penetration wind future are assessed. Although ReEDS scenarios are not forecasts or projections, they provide a common framework for understanding the incremental effects associated with specific power sector changes such as those prescribed in the *Study Scenario*.

ReEDS is specifically designed to represent the unique characteristics of wind generation—variability, uncertainty, and geographic resource constraints—and its impacts on the broader electric system. The model's high spatial resolution[9] and statistical treatment of the impact of variable wind and solar resources enable representation of the relative value of geographically and temporally constrained renewable power resources. In particular, ReEDS explicitly and dynamically estimates and considers the need for new transmission, increases in operating reserve requirements,

8. Alaska, Hawaii, and Puerto Rico are not included in ReEDS analysis. The analysis assumes net energy transfers from Canada to the United States (see Appendix G), but ignores the limited interactions with Mexico. The start year for ReEDS is 2010, but *Wind Vision* results are primarily presented from 2013.

9. ReEDS represents the continental United States using 356 wind resource regions in which wind quality and resource availability are characterized, and 134 model balancing areas. Most other technologies, generator dispatch, load balancing, and other system operation factors are considered within the 134 model balancing areas. In addition, transmission modeling, including power transfers and transmission capacity expansion, occurs between the 134 balancing areas. Transmission expansion within a balancing area is estimated, in this report, for new wind interconnections only. Balancing area boundaries in ReEDS do not correspond identically with actual balancing authority area boundaries.

and changing contributions to planning reserves that may be driven by increases in renewable generation, including wind. ReEDS dispatches all generation using multiple time-slices to capture seasonal and diurnal demand and renewable generation profiles.[10]

In addition to modeling wind technologies (land-based and offshore), ReEDS features a full suite of major generation and storage technologies. This includes coal, natural gas, oil and gas steam, nuclear, biopower, geothermal, hydropower, utility-scale solar, pumped hydropower storage, compressed air energy storage, and batteries.[11] ReEDS applies standardized financing assumptions for investments of all technologies represented in the model. Financing rates assume a weighted average cost of capital of 8.9% (nominal).[12] With this model representation of fossil, nuclear, renewable, and storage technologies, and the treatment of variable generation, ReEDS is able to provide estimates of the impact of greater wind penetration to the system over time.

The ReEDS documentation [3] provides a more detailed description of the model structure and key equations. Recent publications using ReEDS include the U.S. Department of Energy's (DOE's) *SunShot Vision Study* [5], the *Renewable Electricity Futures* study [2], lab reports [6, 7, 8, 9] and journal articles [10, 11, 12, 13].[13] The ReEDS model was also used to develop scenarios for the *20% Wind Energy by 2030* report [1].[14] The model documentation and subsequent publications, however, describe a large number of model developments subsequent to that study.

While ReEDS represents many aspects of the U.S. electric system, it has certain limitations:

- ReEDS is a system-wide optimization model and, therefore, does not consider revenue impacts for individual project developers, utilities, or other industry participants.
- ReEDS does not explicitly model constraints associated with the manufacturing sector. All technologies are assumed to be available up to their technical resource potential.[15]
- Technology cost reductions from manufacturing economies of scale and "learning by doing" are not endogenously modeled for this analysis. Rather, current and future cost reduction trajectories are defined as inputs to the model (see Appendices G and H).
- With the exception of future fossil fuel costs, foresight is not explicitly considered in ReEDS (i.e., the model makes investment decisions based on current conditions, without consideration for how those conditions may evolve in the future).
- ReEDS is deterministic and has limited considerations for risk and uncertainty.
- The optimization algorithm in ReEDS does not fully represent the prospecting, permitting, and siting hurdles that are faced by project developers for either electricity generation capacity or transmission infrastructure.[16]
- ReEDS does not include fuel infrastructure or land competition challenges associated with fossil fuel extraction and delivery.

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10. Each solve year includes 17 time-slices: four diurnal time-slices (morning, afternoon, evening, night) for each of the four seasons (winter, spring, summer, fall) and a summer peaking time-slice.
11. Coal and natural gas with and without carbon capture and storage are included. ReEDS models natural gas combined cycle and combustion turbine technologies independently. Utility-scale solar includes photovoltaic and concentrating solar power with and without thermal energy storage; rooftop solar deployment is not modeled but applied as an exogenous input into the system. Short et al. [3] describes the array of the technologies modeled in ReEDS in greater detail.
12. An additional risk adder is applied to new coal power plant capacity that does not include carbon capture and sequestration to reflect long-term risk associated with potential new carbon or other environmental policies. This approach is consistent with assumptions made in the Energy Information Administration's Annual Energy Outlook 2014 [4].
13. See *www.nrel.gov/analysis/reeds* for a list of publications and further description about ReEDS.
14. The version of the model used in the *20% Wind Energy by 2030* report was referred to as the Wind Deployment System (WinDS) model; ReEDS reflects the current name of the model.
15. ReEDS includes a growth penalty in which the rapid deployment of a technology is penalized with additional capital costs. For wind technologies, this is represented by having capital costs extend beyond the defined amounts if annual capacity additions exceed 1.44 times the additions in the previous solve year.
16. Standard exclusions are applied that limit wind resources below the gross resource potential (see Appendix H). As a linear optimization model, ReEDS also likely underestimates transmission needs due to the lumpiness of real transmission investments and the non-direct paths in real transmission lines compared to the point-to-point model paths. Transmission dispatch modeling in ReEDS, however, includes a linearized DC power flow representation that accounts for non-direct paths of electricity flows.

- ReEDS models the power system of the continental United States and does not represent the broader United States or the global energy economy. For example, competing uses of resources across sectors (e.g., natural gas) are not dynamically represented in ReEDS and end-use electricity demand is exogenously input to ReEDS for the *Wind Vision*.

One consequence of these model limitations is that system expenditures estimated in ReEDS may be understated, as the practical realities associated with planning electric system investments and siting new generation and transmission facilities are not fully represented in the model. Because wind technologies are expected to require new transmission infrastructure development and to benefit from broad-based system coordination, this effect may be amplified when considering high wind penetration scenarios. At the same time, spatial resolution in ReEDS provides sophisticated evaluation of the relative economics among generation resources. It also offers significant incremental insight into key issues surrounding future wind deployment, including locations for future deployment, transmission expansion needs, impacts on planning and operating reserves, and wind curtailments.

ReEDS analysis uses the Solar Deployment System, or SolarDS, model [14] to generate a projection of rooftop solar photovoltaic (PV) deployment. Rooftop PV deployment is then input to ReEDS. All ReEDS scenarios rely on the same single rooftop PV capacity projection.[17] The input parameters for SolarDS used in this analysis are similar to those used in the *SunShot Vision Study* [5], with some exceptions presented in Appendix G. No other distributed generation technologies are modeled explicitly in the *Wind Vision* scenarios, although the unique attributes associated with distributed wind generation are discussed in Section 3.13.[18]

3.1.2 Model Outputs to Assess the Impacts of the *Wind Vision*

Primary *Wind Vision* outputs from the ReEDS model include the location, capacity, and generation of technologies deployed and operated over the period of study (2013–2050). Fixed and operating costs, fuel usage and costs, and other associated costs are also reported, as are transmission infrastructure expansion and related costs. These scenario data are reported in this chapter and are used to inform and support the various impacts assessments, including GHG emissions, other environmental and health benefits, water use, energy diversity and risk, workforce and economic development impacts, and land use. Specific scenario data uses and methods for each impact category are provided in subsequent sections.

ReEDS is also used to estimate electric sector cost implications. Two cost metrics are provided by ReEDS: (1) a nationwide average retail electricity rate, and (2) a net present value system cost. ReEDS estimates electricity prices with a cost-of-service model[19] and accounts for all capital and operating expenses [3] . While this metric is not indicative of actual retail prices in all regions (e.g., price impacts for restructured markets are not evaluated with ReEDS), it provides an indication of the price impacts over time. In addition, annual electricity consumer cost, which is the product of annual rates and end-use consumption, is estimated. The present value system cost metric accounts for capital and operating expenditures incurred over the entire study horizon for all technology types considered, including wind and non-wind generation, transmission, and storage. The cost metrics provided directly from ReEDS do not include any environmental or health externalities (e.g., social cost of carbon emissions).

17. The only differences across scenarios associated with rooftop PV relate to rooftop PV curtailment estimates within ReEDS, which have only minor effects. Rooftop PV capital and operations and maintenance costs are excluded from ReEDS system expenditures. In the case of the *Wind Vision*, however, there is no effect on reported electricity rates or system costs from this exclusion, since results focus on the change in outcomes between two scenarios that do not include these costs in their estimates.

18. A distributed wind deployment model comparable to SolarDS is being developed but was not applied in the *Wind Vision* (see Section 1.2.2).

19. The cost-of-service model assumes a single rate base for the continental United States that includes all capital expenditures amortized over 30 years. Impacts of wind generation on wholesale prices are not estimated for the modeled scenarios and are not described in this section. Text Box 3-6 qualitatively discusses the impacts of wind deployment on wholesale electricity prices. The methodology to estimate electricity prices in ReEDS uses a calibration step to match historical (2010) retail rates to consider distribution costs and/or the markup between wholesale and retail rates for regions with restructured markets. This additional cost is assumed to be uniform across all years and scenarios.

3.1.3 Scenario Framework

The *Wind Vision* modeling analysis is focused on the *Study Scenario* and the *Baseline Scenario*. The *Study Scenario* provides insight into possible high penetration wind futures and allows for description and quantification of effects on the broader electric power sector associated with deployment and operation of a high penetration wind electric system. The *Baseline Scenario* fixes installed wind capacity at year-end 2013 levels and provides the requisite reference from which the incremental impact of all future wind deployment and generation can be assessed. The choice of *Baseline Scenario* as the reference is critical because it allows analysis and quantification of the impacts from all incremental wind energy. None of the scenarios within either of these categories represents a forecast or prediction. Instead, they provide the framework for understanding the impacts in a future that includes high levels of wind power.

Under the *Study Scenario*, annual wind power electricity generation is prescribed to reach pre-determined levels for each ReEDS solve year for the period of 2013 to 2050. Explicit wind electricity generation levels in the *Study Scenario* are 10% of annual end-use electricity demand by 2020, 20% by 2030, and 35% by 2050 (Figure 3-10 illustrates this scenario; Chapter 1 includes a discussion of how this trajectory was developed). While the scenario results are focused on these specific end-point years, wind generation levels are also prescribed for intermediate years by linear interpolation.[20] These values represent the overall national prescriptions and include combined generation from both land-based and offshore wind technologies.

Included within the total wind allotment under the *Study Scenario*, offshore wind generation is prescribed to be 3% of wind's electricity share (0.3% of annual end-use demand) by 2020, 10% of wind generation

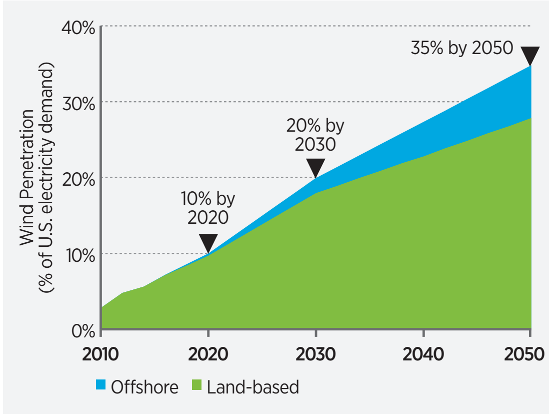


Figure 3-10. Wind penetration levels for the *Study Scenario*

(2% of end-use demand) by 2030, and 20% of wind generation (7% of end-use demand) by 2050. The offshore wind levels include regional specificity for five separate offshore regions: the North Atlantic, South Atlantic, Gulf, Pacific, and Great Lakes.[21]

No predetermined capacity requirements from wind power are modeled in the *Study Scenario.* Total capacity required to reach the wind penetration levels is determined by the assumed future performance (capacity factor) of wind technologies, the quality of the wind resource in sites accessed for each ReEDS scenario, and the amount of wind curtailment estimated by ReEDS.

As noted above, the *Baseline Scenario* constitutes the reference scenario that is used to compare the impacts of wind deployment in the *Study Scenario* and to assess the cost, benefits, and trade-offs of deploying wind relative to other options. In the *Baseline Scenario,* future wind capacity in the continental United States is restricted to be the total installed

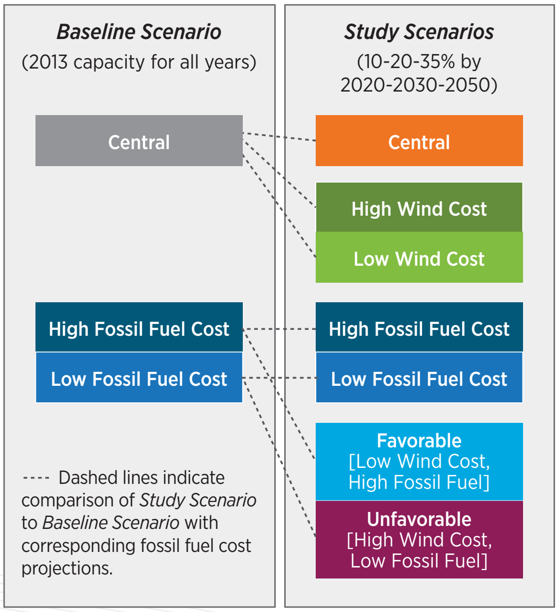
20. The prescribed wind penetration levels for 2016 and 2018 are set to 7.2% and 8.6%, respectively; all other years assume linear increases in wind penetration up to the specific levels established for the three end-point years of 10% in 2020, 20% in 2030, and 35% in 2050.

21. The North Atlantic region includes Atlantic offshore areas from Maryland to Maine. The South Atlantic region includes Atlantic offshore areas from Virginia to Florida, inclusive of only the Atlantic coast of Florida. The Gulf region includes the Gulf coast of Florida and coastal states westward through Texas. The Pacific includes California, Oregon, and Washington. The Great Lakes includes all states touching one of the lakes, but only the westernmost portions of New York. The remainder of New York is considered part of the Atlantic Region. The regional distribution of offshore wind generation is also prescribed for all years. For 2020, the distribution is 80% in the North Atlantic and 20% in the Gulf; for 2030, the distribution is 50% in the North Atlantic, 15% in all other offshore regions except the Pacific, and 5% in the Pacific; and for 2050, the distribution is 33% in the North Atlantic, 22% in the South Atlantic, 20% in the Pacific, 15% in the Great Lakes, and 10% in the Gulf.

capacity as of year-end 2013.[22] As noted, this artificial limit on new wind capacity reflects the fact that the *Baseline Scenario* is constructed exclusively to provide a point of reference relative to the *Study Scenario* and allows an evaluation of the impacts of all *incremental* wind deployment in the *Study Scenario.*

Given uncertainties associated with future market conditions, multiple sensitivities are modeled for both the *Study Scenario* and *Baseline Scenario*. Figure 3-11 shows the scenario framework with ten modeled sensitivities (seven *Study Scenarios* and three *Baseline Scenarios*). Future market variables are limited to wind cost and performance and fossil fuel costs. All other input data assumptions are identical across sensitivities and are described in Section 3.4 and Appendices G and H. These scenario sensitivities allow for increased insight into the robustness of the modeled outcomes, the magnitude of change that may result given uncertainty in specific variables, and the conditions under which a potential change in direction of impact may occur.

Three trajectories of future wind cost—*Central, High,* and *Low Wind Cost*—and three trajectories of future fossil fuel costs—*Central, High,* and *Low Fuel Cost*—are considered. The wind cost trajectories are developed based on ranges provided by multiple independent published projections. The *High Wind Cost* trajectory represents no technology improvement from 2014 for land-based wind and only moderate improvements for offshore wind technology through the mid-2020s, with no further improvements thereafter. The *Low Wind Cost* trajectory represents the low end of cost reductions found from these literature sources. The *Central Wind Cost* trajectory represents the median value. Greater detail on the wind costs are provided in Section 3.4.1 and Appendix H.[23]



Note: Fossil Fuel Costs (Low, Central, High) are based on Annual Energy Outlook 2014 scenarios. Wind costs (Low, Central, High) were derived from a literature review.

Figure 3-11. *Study Scenario* and *Baseline Scenario* framework with associated sensitivities

Similar to the wind costs, the fossil fuel cost trajectories provide a range of future fossil fuel costs and are based on the Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2014 scenarios [4]. In particular, the *Central Fuel Cost* trajectory uses the AEO 2014 Reference Case prices for coal and natural gas; the *High Fuel Cost* trajectory uses the AEO 2014 High Coal Cost and Low Oil/Gas Resource scenarios for coal and natural gas prices, respectively; and the *Low Fuel Cost* trajectory uses the AEO 2014 Low Coal Cost and High Oil/Gas Resource scenarios.

22. The Ventyx Velocity Suite (*http://www.ventyx.com/en/solutions/business-operations/business-products/velocity-suite*) is the basis of all existing installed capacity data for ReEDS for 2010 to year-end 2012. Wind capacity installations in 2013 are based on data from the American Wind Energy Association [15]. The year-end 2013 installed wind capacity represented in ReEDS and included in the *Baseline Scenario* for all post-2013 years totals 60 GW. This differs slightly from the U.S. total of 61 GW estimated by the American Wind Energy Association [15]. Differences are a function of minor discrepancies in the underlying datasets and the exclusion in ReEDS of capacity in Alaska, Hawaii, and Puerto Rico, which is reported in the American Wind Energy Association's total. ReEDS models the continental United States only. These differences have negligible effect on the overall results presented in this analysis. For the *Baseline Scenario,* year-end 2013 installed capacity remains for all future years in that the capacity is automatically repowered upon its assumed lifetime. This differs from the *Study Scenario*, where repowering is a decision made within ReEDS. Repowering garners higher assumed capacity factors, including in the *Baseline Scenario.*

23. Wind technology improvements are characterized through a combination of capital cost reductions, operations expenditure cost reductions, and capacity factor improvements. See Appendix H for additional detail.

Reliance on central assumptions across all model inputs allows the *Central Study Scenario* to be the primary estimate.[24] Figure 3-11 shows the other single-variable sensitivities with assumptions for wind costs (*High Wind Cost*, *Low Wind Cost*) and fossil fuel costs (*High Fuel Cost*, *Low Fuel Cost*) considered independently. Figure 3-11 also shows the multiple variable or combined sensitivities analyzed including the *Favorable* (*Low Wind Costs coupled with High Fuel Cost*) and *Unfavorable* (*High Wind Costs coupled with Low Fuel Cost*) conditions, respectively. When considered together, these multivariable sensitivities are referred to as the *Combined* sensitivities.

The seven *Study Scenario* sensitivities are compared with three *Baseline Scenario* sensitivities. The *Central Baseline Scenario* provides a reference for the three *Study Scenario* sensitivities that rely on the central fossil fuel cost case, and the *Baseline Scenario* sensitivities under *High* and *Low Fuel Cost* assumptions provide references for the *Study Scenario* sensitivities with the corresponding fuel cost assumptions. *Baseline Scenario* sensitivities with different wind technology improvement trajectories are not needed because no new wind capacity is installed.

Many of the results presented in this chapter focus on the full range of analysis sensitivities. Reported impacts including wind capacity additions, economic impacts, electric system impacts, and transmission and grid integration impacts rely on data from the full set of scenario sensitivities modeled. In some instances, impacts are assessed for the *Central Study Scenario* only. For example, GHG benefits, air pollution impacts, water use reduction, workforce and economic development impacts, and energy diversity and risk reduction are calculated solely for the *Central Study Scenario*. Even in those instances in which impacts are calculated based on the *Central Study Scenario,* a range of results is presented to reflect the uncertainties associated with these impacts. Impacts calculated from the full set of scenarios are clearly distinguished from those calculated from the *Central Study Scenario* alone. This distinction is important, but does introduce challenges for direct comparisons across the reported impact metrics.

These scenarios and their respective sensitivities provide a means to quantify the impacts of higher wind deployment. In particular, the scenario framework is designed to provide general bounding assessments specific to wind technology and fossil fuel market variables. Ultimately, however, this framework primarily demonstrates the changes in the results as a function of those variables alone. Other market factors, including electricity demand growth and non-wind power costs, can also impact results and introduce uncertainty; however, modeling the sensitivity of results to these factors is outside the scope of this particular scenario analysis. In addition, other than the prescribed wind penetration levels in the *Study Scenario*, the modeling analysis only considers existing policies as enacted as of January 1, 2014. Proposed or new legislation or regulations that would impact future wind deployment are excluded from the results and analysis reported here. The assumption of no new policies, beyond the prescribed wind penetration levels, does not represent policy forecasts or recommendations. Section 3.2 provides the key input assumptions of the analysis.

It is important to note that—while the *Wind Vision* analysis is policy-agnostic and focused entirely on the electric sector—the impacts, costs, and benefits of the *Study Scenario* and respective sensitivities will be dependent on the policy and market factors used to yield wind deployment levels consistent with the *Wind Vision*, and on larger economy interactions. The impacts, costs, and benefits presented here are driven by the approach to implementing the *Study Scenario* in ReEDS: prescribed wind generation levels in the electric sector. Alternative approaches to reaching the same deployment levels, through policy drivers and/or market dynamics, would be expected to yield different results. Research has generally found that energy policies that are specifically intended to internalize so-called "external" costs (e.g., environmental taxes) are likely to be more cost effective and/or deliver greater social returns than will technology- or sector-specific policy incentives. This is, in part, due to economy-wide rebound and spillover effects. These effects are discussed in Section 3.7, but are not modeled in the *Wind Vision* analysis.

24. Although the *Central Study Scenario* reflects a central estimate, it has not been assigned a higher probability (in fact, no probabilities are explicitly assigned to any single scenario) and should not be construed as a most likely outcome. It is simply the central estimate given the range of potential input variables that exist as of 2013.

3.2 Summary of ReEDS Inputs

The ReEDS model requires a diverse set of inputs. Inputs of particular importance for the *Wind Vision* analysis include generation capacity cost and performance from 2014 to 2050 for wind technologies, other renewable technologies, and non-renewable technologies (e.g., coal, gas, nuclear). Key market variables that also serve as important modeling inputs through 2050 include anticipated generation plant retirements, future load growth, and fossil fuel prices. This section summarizes the values applied for the inputs and, where applicable, describes the methods by which these inputs were developed. Data reflect costs to build and operate new plants only and apply to the *Study Scenario* and the *Baseline Scenario*. For supplemental detail on these inputs, as well as operating costs associated with the existing plants, transmission costs, and storage costs, see Appendices G and H.

3.2.1 Wind Power Technologies

Wind technology inputs applied in this study are grounded in historical trends and published projections of future wind technology cost and performance. They assume continued technology development, optimization, and maturation. Although ReEDS uses explicit capital cost, capacity factor, and operations and financing inputs, this summary of ReEDS inputs reports costs strictly in terms of levelized cost of electricity (LCOE).[25]

Land-Based Wind

Land-based wind inputs were developed by the *Wind Vision* project team and are grounded in reported costs, e.g., [16] and modeled performance of currently available technology e.g., [17]. Primary cost inputs were developed from Interior region data as defined by Wiser and Bolinger [16] to control for non-technology regional cost differences (e.g., variability in labor rates and other non-turbine input costs).[26,27] Capital cost, estimated operating expenditures, and modeled performance data were coupled with high-resolution (200-meter [m]) hourly wind resource data to estimate LCOEs for all potential (non-excluded)[28] resource sites in the continental United States. Estimates of LCOE across a full array of potential project sites are required as a result of the multi-decadal time period covered by the analysis.

The *Wind Vision* project team also developed land-based wind LCOE projections through 2050. Projections were derived from a review and analysis of independent literature projections. More than 20 projection scenarios from more than 15 independent studies were considered (see also [18, 19]). Individual LCOE projections were estimated, extracted, and normalized to a common starting point using a process similar to, e.g., Lantz et al. 2012 [18]. This process resulted in an overall range of projected land-based LCOE reductions of 0–40% through 2050. From these results, three explicit projections were selected for modeling:

- *High Wind Costs*: Constant wind LCOEs from 2014 to 2050
- *Central Wind Costs*: Median annual cost reduction identified in the literature
- *Low Wind Costs*: Maximum annual cost reduction identified in the literature

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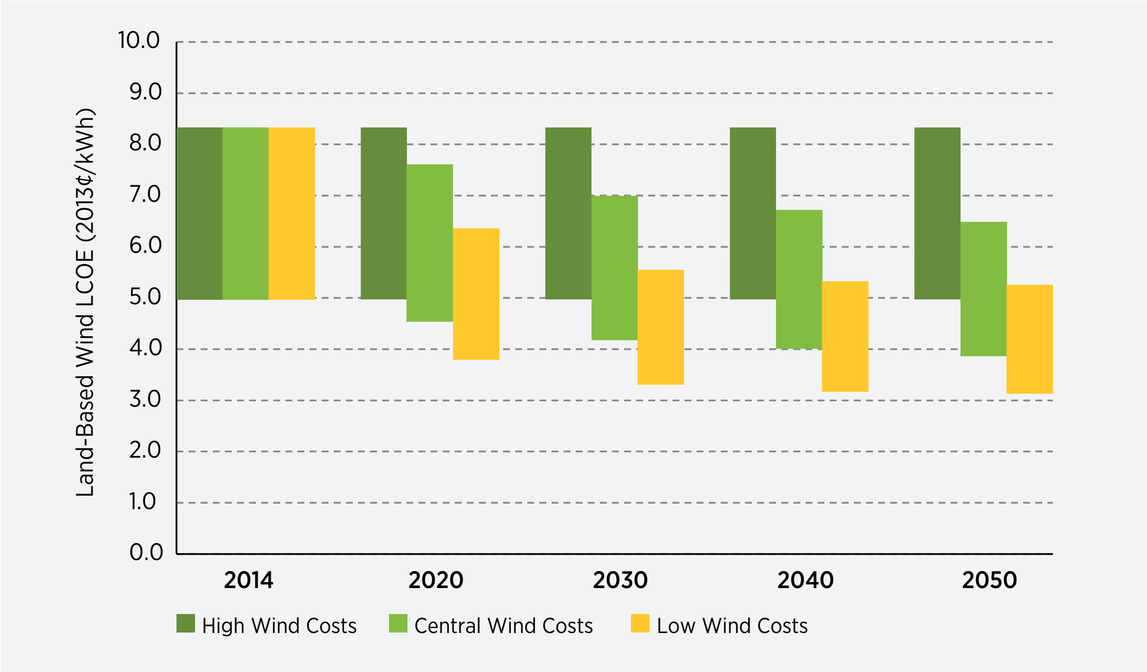
25. Although there are various metrics that can be used to report generation costs, LCOE represents the present value of total costs divided by the present value of energy production over a defined duration (20 years in the referenced analysis). Actual disaggregated inputs are contained in Appendices G and H. LCOE values shown reflect permanent elements of the tax code (e.g., Modified Accelerated Cost Recovery System, or MACRS) but exclude policy support requiring periodic re-authorizations, such as the wind Production Tax Credit, as well as specific state policy support mechanisms (e.g., Renewable Energy Credits, property tax abatements, sales tax abatements). LCOE values should not be construed as representative of all system or societal costs. ReEDS modeling and subsequent impacts. assessment detailed in Sections 3.4–3.13 represent a more complete accounting of electric system and societal impacts.
26. The Interior region selected here is consistent with the Interior region as defined by Wiser and Bolinger for industry reporting in the 2012 Wind Technologies Market Report [16]. This region comprises states from the Rocky Mountains east to the Mississippi River, excepting Arkansas and Louisiana, which are grouped as part of the Southeast.
27. While ReEDS inputs are derived from empirical Interior region cost data, the ReEDS model adjusts for regional differentials in cost as well as the cost to move energy from a wind resource site to load either as a function of local spur lines or long-distance interstate transmission (see also Appendix G).
28. Excluded land areas include urban areas, national parks, highly sloped land areas, and others. For a full list of resource exclusions, see Appendix H.



Note: Ranges result from consideration of a broad array of wind speed conditions. For areas outside the Interior region, capital cost multipliers are applied, resulting in a broader range of estimated costs for the country as a whole than reflected here. Data shown represent the plant-level LCOE, excluding potential intraregional transmission needed to move the power to the grid and interregional transmission to move the power to load.

Figure 3-12. Land-based wind changes in LCOE by sensitivity (2014–2050, Interior region)

Figure 3-12 illustrates the range of land-based wind LCOEs represented in the *Wind Vision* scenario framework for the Interior region and related changes from 2014 to 2050.[29] Data shown represent plant-level LCOE, excluding potential intraregional transmission needed to move the power to the grid and interregional transmission to move the power to load. Ranges reflect the variability in resource quality captured within the ReEDS model. Changes from 2014 LCOEs are 0% by 2050 under *High Wind Costs*; 9% by 2020, 16% by 2030, and 22% by 2050 under *Central Wind Costs*; and 24% by 2020, 33% by 2030, and 37% by 2050 under *Low Wind Costs*. Additional detail regarding the development of land-based wind costs as well as explicit ReEDS capital costs, capacity factors, and operations costs are detailed in Appendix H. For insights into the comparability of these inputs with current market data, see Text Box 3-1.

Offshore Wind

Offshore wind inputs were developed in a similar manner as their land-based counterparts. A greater diversity of technology (e.g., shallow water versus deepwater), limited data, a less mature industry, and fewer long-term projections necessitated some key differences. Data limitations are particularly significant for mid-depth (30–60 m) and deepwater (60–700 m) sites.

Starting-point cost data were derived from the published data of the global offshore wind industry as well as estimates from recent development activity on the Atlantic coast of the United States [23, 19]. These data were coupled with engineering assessments and distance-based cost functions (specific to the offshore export cable and incremental construction cost associated with moving farther from shore) to determine expected site-specific costs for technology across a broad range of water depths and distances

29. All dollars are in real 2013$ unless otherwise noted.

Text Box 3-1.

Benchmarking *Wind Vision* Inputs with Expected Costs for Current Projects

Estimated wind technology ReEDS LCOEs developed from the methods described in Section 3.2.1 were compared with 2012 historical market power purchase agreement (PPA) data and PPA data for projects scheduled to come online in 2014-2016. Although this benchmarking exercise is limited by the standardized financing terms applied in ReEDS (Appendix H) and the resulting simplified representation of the value of the PTC in the ReEDS LCOE values, it offers the opportunity for basic validation of the *Wind Vision* analysis inputs. Benchmarking results are reported only for resource areas best represented by the locations where active development is concentrated today and assumes Interior region costs.

Assuming qualification for the PTC, estimated ReEDS LCOEs for projects in the Interior region likely to have been commissioned in 2012 range from approximately $27/megawatt-hour (MWh) to $38/MWh. The interior region generation weighted average market PPA price for projects signing contracts in 2012 was approximately $31/MWh with a range of approximately $20/MWh to $40/MWh [20]. Estimated ReEDS LCOEs for projects likely to be commissioned in 2014–2016 (and qualifying for the PTC) range from $24/MWh to $35/MWh in the *Central Wind Cost* case and $18/MWh to $29/MWh in the *Low Wind Cost* case. Recent Interior region PPA price data (contracts signed in 2013–2014) for projects to be delivered in 2014–2016 indicate a generation weighted average of approximately $23/MWh with an approximate range extending from below $20/MWh to about $30/MWh [20]. These simple comparisons suggest that ReEDS LCOE alignment with 2012 market PPA data is strong; ReEDS LCOEs also appear to be relatively consistent with 2014–2016 market data, particularly when considering the range offered by the *Low Wind Cost* case.

The standardized ReEDS financing assumptions reflect long-term electric generation financing cost estimates. This long-term perspective results in slightly greater financing costs (~100 basis points) than are observed in the market today. In contrast, the ReEDS financing assumptions also reflect the full nominal value of the PTC. Based on the work of Bolinger [21] and Bloomberg New Energy Finance [22], the cost of tax equity and lower project debt levels required to monetize the tax credits may erode as much as 30% of the full nominal value of the PTC. Accordingly, without the PTC, the costs represented in ReEDS may be modestly conservative when compared to market expectations for projects in the latter half of this decade.

Given somewhat variable historical pricing trends as well as a tendency for wind and other generation prices to be influenced by market factors (e.g., the cost of generation from natural gas–fired plants), some degree of conservatism is merited within the context of the current scenario analysis. There are other modeling elements that could be weighed against any perceived conservatism in terms of individual project cost representation. These factors include environmental and wildlife exclusions that do not fully represent the near-term challenges associated with building on federal public land or in other environmentally sensitive regions, as well as the ability for the ReEDS model to select among a vast array of project sites with no transaction costs or associated sunk costs.

from shore.[30] Modeled performance data for state-of-the-art technology available as of 2013 were also compiled. As was done for land-based wind, estimated capital costs, operations expenditures, and performance data were applied to high-resolution hourly wind resource data to estimate LCOEs for all potential (non-excluded) offshore wind resource sites. Applying the standardized financing assumptions, ReEDS LCOEs range from approximately $170/MWh to $230/MWh for shallow-water sites as of 2013.[31] If current market-based financing assumptions (e.g., a weighted average cost of capital of approximately 10%–11% nominal) were applied, this LCOE range would increase by approximately $20/MWh to $30/MWh. These estimates can be compared with contracted sales prices for offshore wind as reflected in PPAs. Pricing ranged from $180/MWh to $245/MWh (2013$) for projects in the United States under development as of 2013 (see also Chapter 2).

Offshore wind LCOE projections through 2050 were developed using a combination of methods. Review and analysis of independent literature-based projections were used to inform estimates of cost reduction through the mid-2020s [24, 25, 26].[32] Beyond the mid-2020s, offshore wind projections rely on three independent learning rate estimates to project costs from the mid-2020s to 2050.[33] Common learning rates were applied independent of site-specific impacts on technology (e.g., water depth, geotechnical considerations, distance from staging area). For the *High Wind Cost* inputs, a 0% learning rate is assumed; in effect, no further improvements are considered.[34] For the *Central Wind Cost* inputs, a 5% learning rate is assumed. This 5% rate is generally consistent with rates projected by van der Zwaan et al. [27]. For the *Low Wind Cost* inputs, a 10% learning rate is assumed, consistent with estimates for the global wind industry by Wiser et al. [28] and Musial and Butterfield [29]. Learning rates are applied to estimated global capacity assuming a compound average annual growth rate of approximately 10% from 2013 to 2050.[35]

Figure 3-13 illustrates the range, as a function of wind resource quality and water depth, of offshore wind LCOEs in the *Wind Vision* scenario framework, and how these LCOEs change from 2014 to 2050. Data represent the plant-level LCOE, excluding the marine export cable, potential intraregional transmission needed to move the power to the grid, and interregional transmission to move the power to load. Changes from 2014 LCOEs are 5% by 2020, 18% by 2030, and 18% by 2050 under *High Wind Costs*; 16% by 2020, 32% by 2030, and 37% by 2050 under *Central Wind Costs*; and 22% by 2020, 43% by 2030, and 51% by 2050 under *Low Wind Costs*. Additional detail regarding the development of offshore wind costs as well as explicit ReEDS capital costs, capacity factors, and operations costs are available in Appendix H.

Given the data limitations and relative immaturity of offshore wind technology, a number of caveats should be considered for these estimated cost data. First, cost reductions presented here are based on the methods described. Apart from what is reflected in the literature for expectations through the mid-2020s, the approach has not considered explicit innovation opportunities. This is particularly notable for deepwater technology (60–700 m)—and, to a lesser degree,

30. Site-specific estimates did not consider regional cost multipliers or land-based grid infrastructure costs. The purpose of the base cost characterization and data binning was to rank sites based on their cost of energy delivered to shore, neutral of non-technical market cost drivers (e.g., variable labor costs by region). Both non-technical market cost drivers and land-based grid infrastructure costs are separately captured in the ReEDS model (see Appendix G).

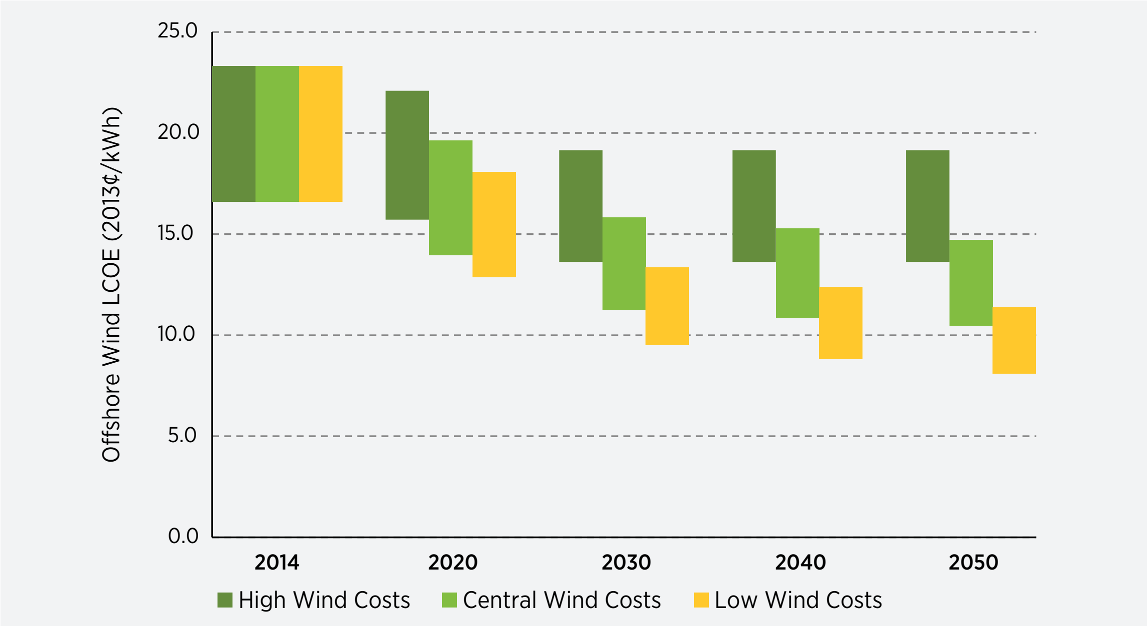
31. ReEDS standardized financing costs were applied to calculate LCOEs. As such, actual LCOEs are likely underestimated for projects under development in U.S. waters as of 2014. Nonetheless, implicit in the standardized ReEDS financing costs is the assumption that industry and technology maturation will bring parity in all energy infrastructure financing costs.

32. Literature projections were not applied to the long term because only a small sample of projections extend beyond the mid-2020s and representation of recent industry trends in those studies is poor.

33. Learning rates rely on historical trends to project future technological improvement. The learning rate is defined as the percent change in cost for every doubling in cumulative production or units installed. Wiser et al. [17] provide a detailed review of learning rates as such rates apply to wind energy.

34. Given the current maturity of offshore wind technology, this learning rate assumes very limited or no industry growth outside of the United States and, in many respects, an inability for the industry to achieve adequate scale and volume required to reduce costs.

35. Actual compound average annual growth rate is expected to decline with time, achieving potentially 30% in the near term but declining to 5% sometime after 2030. Near-term growth is generally expected to develop in Europe and China, with the United States, Japan, and other countries potentially supporting growth in 2020 and beyond.



Note: Consistent with land-based wind cost estimates, ranges result from consideration of a broad array of wind speed conditions. In addition, regional multipliers are applied to offshore wind capital costs. As a result, actual generation costs represented in ReEDS vary from those shown in this figure, at levels consistent with regional variability in labor rates and other non-turbine input costs. Data shown represent the plant-level LCOE, excluding the marine export cable, potential intraregional transmission needed to move the power to the grid, and interregional transmission to move the power to load.

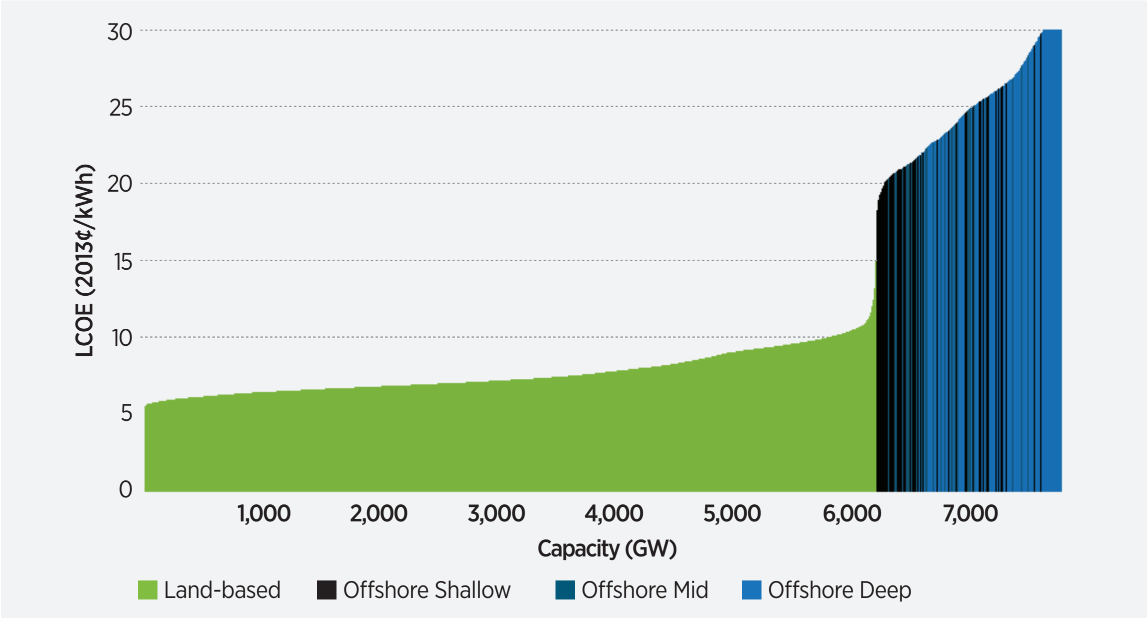
Figure 3-13. Offshore wind changes in LCOE by sensitivity (2014–2050)

mid-depth technology (30–60 m)—as the literature is principally focused on fixed-bottom shallow-water technology and may understate the overall long-term cost reduction potential for other, deeper-water offshore technologies. Second, the use of learning curves to derive the long-term projections requires estimates of global installed capacity. Such estimates are highly uncertain, since future deployment will depend on the cost of competing alternatives as well as on potential GHG or other environmental commitments which may spur additional deployment of renewable energy. Finally, the learning rates chosen reflect a range of estimates derived from literature [27, 30] and the experience of land-based technology [29, 28]. While empirical learning rates for offshore wind have not yet been developed given the nascent status of the industry, it is likely that actual offshore learning rates will differ from those applied here.

Despite these limitations, the cost trajectories associated with wind technology sensitivities provide a broad range of cost reduction potential for offshore wind. While it is possible that cost reductions greater than those examined here may be realized, the results demonstrate the substantial and continued need for innovation and maturation in the offshore wind industry.

Figure 3-14 combines existing cost estimates for land-based and offshore wind with high-resolution wind resource data to develop a supply curve or illustration of the total resource potential for wind at various LCOE levels. The supply curve considers the array of wind resource quality groups represented in ReEDS, as well as various environmental or other exclusion areas (described in Appendix H). Resource quality groups are denoted here as Techno-Resource Groups, as they consider both wind resource and applicable technology design considerations.[36] To place these numbers in context, the U.S. electric system currently includes approximately 941 GW of installed electric capacity across all technologies.

36. See Appendix H for an expanded description of Techno-Resource Groups, as well as regional capital costs and performance characteristics, interconnection costs, and other regional factors.



Note: LCOE estimates exclude the PTC or investment tax credit.

Figure 3-14. Combined land-based and offshore wind resource supply curve, based on estimated costs in 2012

3.2.2 Other Renewable Power

Expected cost and performance estimates for new solar PV, concentrating solar power, geothermal, biomass, and hydropower were also developed from empirical market data and literature projections, where such data were available. Some methodological deviations were required given data limitations, resource constraints, and intrinsic differences in technology and resource requirements. A single cost and performance trajectory was developed for each renewable technology and applied across the full set of modeled scenarios.

Solar power capital costs were benchmarked to cost data reported by Bolinger and Weaver [31] and GTM Research/Solar Energy Industries Association [32]. Capital cost projections from 2013 to 2020 are aligned with the 62.5% reduction scenario (from 2010 levels) documented by DOE [5]. This cost trajectory was subsequently grounded against a sample of cost projections from the EIA [33], International Energy Agency [26], Bloomberg New Energy Finance [34], Greenpeace/European Photovoltaic Industry Association [35], GTM Research/Solar Energy Industries Association [36, 32]. From 2020 to 2040, costs decline to $1.20/AC watts ($W_{AC}$) for utility-scale PV, to $1.90/$W_{AC}$ for distributed residential rooftop PV, and to $3.60/$W_{AC}$ for concentrating solar power.[37] Although there are fewer literature estimates that emphasize this time period, this cost trajectory was also generally consistent with an average literature estimate [26, 34, 33]. Costs were assumed to be unchanged (in real terms) from 2040 to 2050.[38] Performance for all solar technologies varies regionally and is based on solar irradiance data from the National Solar Radiation Database.[39]

Hydropower is represented in the current analysis by the most recent national-scale resource potential estimates for non-powered dams [37] and undeveloped sites [38]. Resource estimates exclude upgrades and expansions at existing facilities and new sites less than 1 MW.[40] Costs are derived from methods developed by

37. Costs reported here in AC watts are consistent with targets under DOE's SunShot Initiative, e.g., $1.00/DC watt for utility-scale PV (*http://energy.gov/eere/sunshot/sunshot-initiative*).

38. Potential justifications for flat cost over this time period include increasing uncertainty with time and diminishing returns from research and development investment.

39. The National Solar Radiation Database is available at *http://rredc.nrel.gov/solar/old_data/nsrdb*.

40. Marine hydrokinetic technologies are also excluded from the analysis.

the Idaho National Laboratory and are consistent with cost representations applied in the EIA's AEO [4] as well as past ReEDS analysis, including the *Renewable Electricity Futures* study [2].[41]

Geothermal resources represented in ReEDS include identified hydrothermal resources and near-hydro-thermal field enhanced geothermal systems consistent with the EIA AEO 2014 Reference Case and Augustine et al. [39]. All other potential geothermal resource areas are excluded. Current costs and total available potential are detailed by Augustine et al. [39]. Given substantial uncertainty in future cost trends, costs are constant for the period of analysis.[42]

Biomass power represented in ReEDS includes both co-fired and dedicated biomass units. Cost and performance estimates are derived from the EIA AEO 2014 Reference Case. Supplemental detail is provided in Appendix G.

3.2.3 Non-Renewable Power Technologies

Non-renewable electric generation technologies, including coal, natural gas combined cycle, natural gas combustion turbine, and nuclear technologies, rely on capital cost and performance estimates resulting from the EIA AEO 2014 Reference Case. Cost and performance estimates for natural gas combined cycle with carbon capture and storage, and for coal with carbon capture and storage, are consistent with those from the EIA AEO 2014 Reference Case. Full detail on these inputs is in Appendix G.

3.2.4 Market Variables

Other power sector variables also play a role in determining the associated impacts of the *Study Scenario*. Of particular significance are expected retirements, changes in demand for electricity generation, and future fossil fuel prices.

Retirements

Retirements in ReEDS are primarily a function of plant age and assumed lifetimes. Fossil fuel-fired plant ages are derived from data reported using Ventyx.[43] Coal plants less than 100 MW in capacity are retired after 65 years; coal plants greater than 100 MW in capacity are retired after 75 years. Natural gas- and oil-fired capacity is assumed to have a 55-year lifetime. Nuclear plants are assumed to be approved for a single service life extension period, giving existing nuclear plants a 60-year life.[44] No refurbishment costs or increased operations and maintenance (O&M) costs are applied to extend the nuclear or fossil plant life. Figure 3-15 details the resulting age-based retirements across existing coal, oil and gas steam turbines, nuclear, and gas-fired capacity (natural gas combined cycle and natural gas combustion turbine), as well as the share of existing 2012 capacity retired throughout the period of analysis. These assumptions result in retirement by 2050 of nearly all of the existing oil and gas steam turbine and nuclear fleets, and about half of the existing coal fleet.

Plant lifetimes are also estimated for newer generation sources. Respective assumed lifetimes are: wind power plants, 24 years; solar and geothermal facilities, 30 years; and battery storage, 12 years. All other technologies (e.g., hydropower, biopower) are assumed to have lifetimes extending beyond 2050. While all generator types retire at the end of their defined equipment lifetimes, the site-specific technologies that have resource accessibility supply curves (wind, solar, geothermal) require some special consideration. When a parcel of capacity retires (for instance, some wind capacity retiring upon reaching its assumed 24-year life), the freed resource potential in that site is available for new builds. This new build is assumed to have no accessibility cost, since the spur line and other site infrastructure developed for the original plant can be re-used for any new builds on these sites.

41. Ongoing DOE work is expected to provide insight into the long-term potential for hydropower electricity capacity and generation at a level that is not reflected in the present study or modeling treatment (*http://energy.gov/eere/water/new-vision-united-states-hydropower*).

42. While an endogenous treatment of technology learning from the National Energy Modeling System model is used for the AEO reports, it is not included in the present ReEDS analysis. As such, the geothermal technology costs used here differ slightly from the costs reported in the AEO.

43. *http://www.ventyx.com/en/solutions/business-operations/business-products/velocity-suite*

44. A single service life extension period was selected as a central assumption given significant uncertainty in current nuclear plant lifetimes. High uncertainty persists due to the potential for new investments that might be required to keep existing plants in operation (e.g., San Onofre) as well as marginal operations costs that may not be supported by current wholesale power prices. At the same time, the possibility for a single or perhaps even double service life extension remains, given perceived GHG risks [4] .

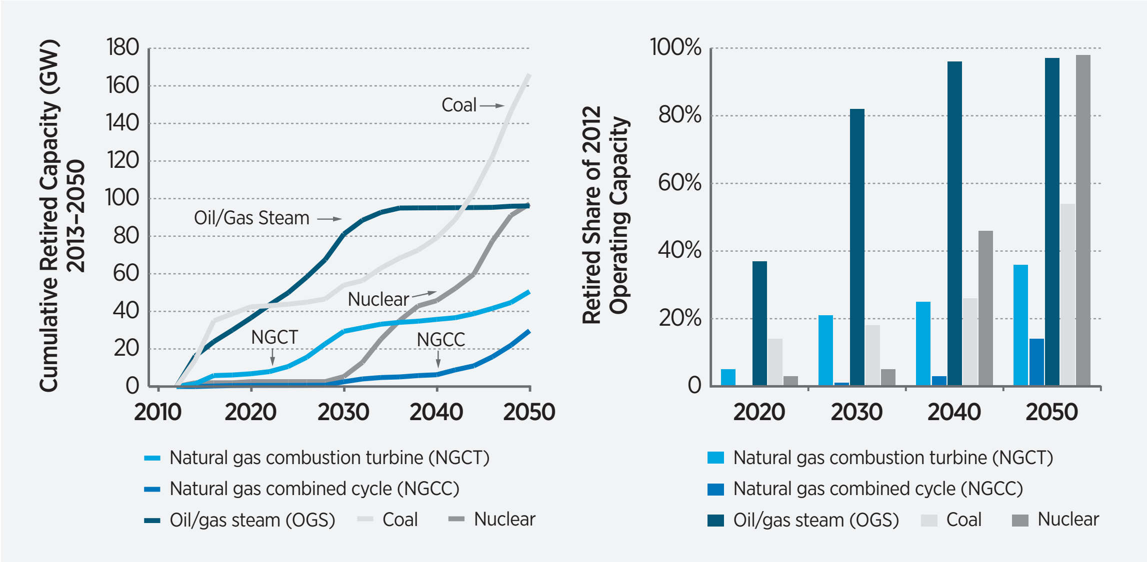


Figure 3-15. Estimated age-based and announced cumulative retirements and retirements by share of the operating fleet

In addition to age-based retirements, other near-term coal retirements are reflected in the modeled scenarios by incorporating announced retirements [40],[45] and long-term retirements are incorporated by considering plant utilization. As illustrated in Figure 3-15, assumed age-based and announced coal retirements total 42 GW of coal capacity retirements from 2013 to 2020, 54 GW by 2030, and 166 GW by 2050.[46] Modeled utilization-based coal retirements represent a proxy for economic-based considerations and accelerate coal retirements. For example, cumulative (starting in 2013) coal retirements in the *Central Study Scenario* total 43 GW by 2020, 67 GW by 2030, and 186 GW by 2050.[47]

Degradation of the efficiency of solar PV capacities over time is also modeled at 0.5% per year [44]—i.e., the capacity of PV that generates energy is reduced by 0.5% every year. In the *Wind Vision* analysis, however, the total PV capacity reported does not reflect this degradation and remains at initial capacity. Instead, the generation reported from this capacity is reduced, reflecting the efficiency degradation of that capacity over time.

Load Growth

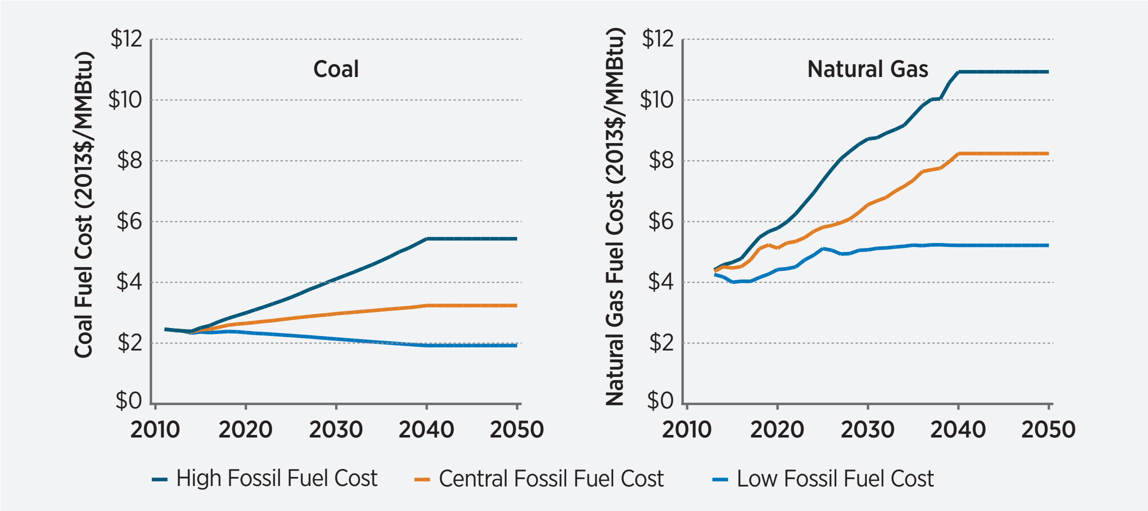
The *Wind Vision* analysis applies a single load growth trajectory. Load growth in the *Wind Vision* is assessed by the change in end-use electricity demand and is based on the EIA's AEO 2014 Reference Case. Load growth is extracted from the AEO 2014 Reference Case for the time period of 2013 to 2040, and is extrapolated through 2050.[48] Regional differences reflected by the AEO are also represented in ReEDS. The overall change in electricity demand associated with this scenario is approximately 34% from 2013 (3,700 terawatt-hours [TWh]) to 2050 (4,900 TWh) and averages 0.8% per year. Growth is generally linear from 2013 to 2050.

45. Due to ReEDS geospatial requirements, these data reflect announced retirements only (e.g., [40]). Other estimated retirements (e.g., [41, 42, 43]) lack sufficient geospatial and temporal resolution to be incorporated into ReEDS, but are addressed to a degree by overlaps with Saha [40], and by the age-based and plant utilization-based retirements.

46. Age-based and announced coal retirements from 2010 (the ReEDS model start year) to 2020 total 57 GW. A direct comparison of this assumption with other literature (e.g., [41, 42, 43]) is difficult, as the starting year is not consistent across references.

47. Under the *Baseline Scenario,* coal capacity experiences greater utilization. Thus, fewer retirements are observed to occur across *Baseline Scenario* sensitivities compared with the *Study Scenario.*

48. The method and data sources used to both calibrate the 2010 ReEDS start year load profiles and extrapolate to future years (see Appendix G) lead to slight differences to the end-use demand trajectory in ReEDS compared to the AEO 2014 Reference Case projection. These differences have negligible effect on the scenario results.



Source: EIA, 2014 [4]

Figure 3-16. Base coal and natural gas fuel cost trajectories applied in the *Wind Vision*

Fossil Fuel Costs

A range of fossil fuel costs (coal and natural gas) are applied in the *Wind Vision* analysis. Three explicit trajectories are considered: *Low Fuel Costs*, *Central Fuel Costs*, and *High Fuel Costs*. This approach is intended, in part, to reflect the substantial uncertainty in future fuel cost projections and the sensitivity of future modeling outcomes to changes in the projected fossil fuel prices. Fuel cost scenarios are grounded in the work of the EIA and published in AEO 2014 [4].

Central Fuel Costs are extracted from the AEO 2014 Reference Case; *Low Fuel Costs* are extracted from the High Oil and Gas Resource and the Low Coal Cost scenarios in the AEO. *High Fuel Costs* are extracted from the Low Oil and Gas Resource and High Coal Cost scenarios in the AEO. Because the AEO data extend only through 2040, fossil fuel costs for each specific trajectory (i.e., *Low, Central, High*) are assumed to be constant in real dollar terms from 2040 to 2050.[49] Constant cost treatment during this time period is justified based on the high uncertainty associated with 2040 prices and the overall price levels also projected in 2040. Figure 3-16 illustrates these cost trends for the full period of the analysis.

Values shown in Figure 3-16 represent the national ReEDS model inputs. In the *Wind Vision* analysis, however, more highly resolved regional data are applied. Natural gas cost adjustments are also incorporated in ReEDS to account for the sensitivity of fuel costs (prices) to changes in regional electric sector fuel usage (see also [11] and Appendix G).

3.2.5 Policy Assumptions

Existing policies are represented as enacted as of January 1, 2014. All state renewable portfolio standards (RPSs) are modeled, federal tax incentives are included as they exist on January 1, 2014, and accelerated depreciation rules that exist as a permanent part of the tax code are reflected in the cost of new technologies. The wind PTC and investment tax credit (ITC) are assumed to be expired without further extensions. The Modified Accelerated Cost Recovery System depreciation schedules remain in place through 2050. The solar ITC is assumed to be 30% until after 2016, after which it is assumed to remain at 10% through 2050. The geothermal ITC is assumed to be 10% for all years. California's Assembly Bill 32, or AB32, is modeled.[50,51]

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49. Prices are assumed to increase with the rate of inflation over this time period.

50. California Assembly Bill 32 is modeled in ReEDS as a carbon cap for the electricity sector. The cap limits are derived from California emissions in the AEO 2013 Reference scenario [33] and consider in-state generation as well as imports from outside of California. Other regional, state, or local carbon cap-and-trade systems, including the Regional Greenhouse Gas Initiative, are not represented.

51. In the *Baseline Scenario,* the model treatments of existing state policies (RPSs and California AB32) are modified to reduce cost distortions that these state policies would have when wind is not available to meet these standards.

No new policies, including new or proposed environmental regulations, are explicitly modeled; however, wind penetration levels are enforced in the model. U.S. Environmental Protection Agency (EPA) regulation is partially represented in the announced retirements captured by the model (Section 3.2.4).[52] The EPA's proposed Clean Power Plan is not modeled directly in ReEDS.

Modeling and associated cost and price impacts presented here do not consider future limits to criteria pollutants or carbon dioxide (CO_2).[53] However, environmental impacts from reduced air pollution and GHG as a function of the *Study Scenario* are quantified and monetized in Sections 3.7 and 3.8.

This approach allows for a consistent estimation of the costs, benefits, and impacts of the *Wind Vision* scenarios. However, it does not reflect a policy recommendation, expectation, or preference. Moreover, the impacts, costs, and benefits of the *Wind Vision* will be somewhat dependent on the policy and market variables used to achieve wind deployment, as discussed in Section 3.3. Text Box 3-3 provides added context on current and past government incentives for energy supply.

3.2.6 Summary of Inputs

The ReEDS inputs discussed in previous sections of 3.2 are summarized in Text Box 3-2 for reference in future sections.

As introduced in Section 3.1.3, a number of sensitivities were analyzed to understand the range of potential impacts of the *Study Scenario*. The upcoming sections—3.3 Wind Capacity Additions, 3.4 Economic Impacts, 3.5 Electricity Sector Impacts, and 3.6 Transmission and Integration Impacts—present results for the *Central Study Scenario* as well as some of the sensitivities summarized.

52. A sulfur dioxide cap is also included in ReEDS (see Section 3.8).

53. A risk factor applied to new investments in coal-fired capacity without carbon capture and storage is included to capture the potential for new carbon policy (see Appendix G).

Text Box 3-2.

Impacts Analysis Scenario Framework and Inputs Summary

The *Wind Vision* uses scenarios to explore the range of potential impacts that could result from increased deployment of wind power as defined in the *Study Scenario*. *Study Scenario* impacts are generally assessed relative to the *Baseline Scenario*, with limited exceptions for specific metrics (e.g., land use is assessed for the total installed wind capacity in the *Study Scenario*). To assess the robustness of the results, additional scenario sensitivities were conducted, focusing on changes in wind costs and fossil fuel costs independently and in combination. These sensitivities are designed to inform the range of outcomes. Table 1 defines the key modeling constants across scenarios. Table 2 summarizes the scenarios considered and highlights their differences.

Table 1. Constants Across Modeled Scenarios

Input Type	Input Description
Electricity demand	AEO 2014 Reference Case (average annual electric demand growth rate of 0.8%)[a]
Fossil technology and nuclear power	AEO 2014 Reference Case
Non-wind renewable power costs	Literature-based central 2013 estimate and future cost characterization
Policy	As legislated and effective on January 1, 2014
Transmission expansion	Pre-2020 expansion limited to planned lines; post-2020, economic expansion, based on transmission line costs from Eastern Interconnection Planning Collaborative

a. Modeling work described in Chapter 1 to inform the development of the *Study Scenario* included sensitivities in which electricity demand was varied. See Chapter 1 for additional details.

Continues next page

Text Box 3-2. *(continued)*

Impacts Analysis Scenario Framework and Inputs Summary

Table 2. Scenario Definition and Variables

Scenario Label	Description	Inputs
Central Study Scenario	This scenario applies the *Study Scenario* wind trajectory of 10% wind by 2020, 20% by 2030, 35% by 2050 and *Central* modeling inputs. It is the primary analysis scenario for which impacts are assessed and reported.	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Reference Case Wind power costs: Median 2013, with cost reductions derived from literature review
Central Baseline Scenario	This scenario applies the *Baseline Scenario* constraint of no new wind capacity. This scenario also relies on central inputs and is the primary reference case from which impacts are assessed and reported.	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Reference Case Wind power costs: Median 2013, with cost reductions derived from literature review
High/Low Fossil Fuel Cost Study Scenario	These scenarios examine the sensitivity of changes in fossil fuel costs to the results of the *Study Scenario*. Modeling outcomes are compared with the *Baseline Scenario* that includes the respective fossil fuel cost assumptions.	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Low/High Oil and Gas Resource Case and AEO High/Low Coal Cost Case Wind power costs: Median 2013, with cost reductions derived from literature review
High/Low Fossil Fuel Cost Baseline Scenario	These scenarios examine the sensitivity of changes in fossil fuel costs to the results of the *Baseline Scenario*. Modeling outcomes are compared those derived from the *Study Scenario* with the respective fuel cost assumptions.	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Low/High Oil and Gas Resource Case and AEO High/Low Coal Cost Case Wind power costs: Median 2013, with cost reductions derived from literature review
High/Low Wind Cost Scenario	These scenarios examine the sensitivity of the *Study Scenario* results to changes in wind power cost reductions from 2014–2050. Results are compared to the *Central Baseline Scenario*, which holds wind capacity constant at current levels and is therefore unaffected by changes in wind costs.	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Reference Case Wind power costs: No change in costs from 2014–2050; Max. literature-based change in costs from 2014–2050
Favorable Scenario Study Scenario	By combining low wind costs with high fossil fuel costs, this sensitivity represents the conditions most conducive to wind deployment considered in the analysis and forms a low cost bookend for the *Study Scenario*. Results are compared to the *High Fossil Fuel Cost Baseline Scenario.*	All constants noted in Table 1 Fossil fuel costs: AEO 2014 Low Oil and Gas Resource Case and AEO High Coal Cost Case Wind power costs: Max literature-based change in cost from 2014–2050
Unfavorable Study Scenario	By combining high wind costs with low fossil fuel costs, this sensitivity represents the conditions least conducive to wind deployment considered in the analysis and forms a high cost bookend for the *Study Scenario*. Results are compared to the *High Fossil Fuel Cost Baseline Scenario.*	All constants noted in Table 1 Fossil fuel costs: AEO 2014 High Oil and Gas Resource Case and AEO Low Coal Cost Case Wind power costs: No change in cost from 2014–2050

Text Box 3-3.

Government Incentives for Energy Supply

The United States has a long history of offering incentives at both the federal and state levels for energy development, technologies, and use. In the early days of oil and gas development, Congress adopted policies allowing favorable tax accounting practices; coal similarly received support through favorable tax policy (e.g., [45]). Nuclear energy was initially indirectly supported through military efforts, later leading to commercial reactors for electricity generation. Favorable tax policy applies to nuclear energy, and the Price-Anderson Act was established to partially indemnify the nuclear industry against liability claims arising from nuclear incidents (e.g., [46]).

Federal energy research and development (R&D) has also existed for many decades. A 2012 Congressional Research Service report reviewed available data on R&D funding and found that, "[f]or the 65-year period from 1948 through 2012, nearly 12% went to renewables, compared with 10% for efficiency, 25% for fossil, and 49% for nuclear" [47]. The overall proportion of R&D funding for renewable energy has, however, increased in years leading up to 2014 [47]. Renewable energy has also benefited from favorable federal tax policy and a variety of state-level incentives.

Some widely cited goals of government incentives include: (1) addressing the environmental effects of energy technologies, (2) reducing barriers to the development and adoption of innovative technologies, (3) creating opportunities for local economic development benefits, and (4) increasing energy security and diversity. The relative importance of these goals—and the extent to and efficiency with which various incentives achieve them—is the subject of continual debate. Research has generally found it to be more cost-effective to address market failures (e.g., unpriced environmental effects) directly through policies (e.g., environmental taxes) specifically intended to internalize these "external" costs, rather than solely through technology- or sector-specific incentives (e.g., [48,49, 50, 51]).

One question that often arises is the relative size of incentives for different energy technologies. Studies conducted as of 2013 have led to widely varying estimates as a result of three types of complications. First, the definition of what is considered an energy incentive varies widely. Some incentives—such as federal direct spending via grants, favorable taxation, and R&D—are almost always included, whereas others, such as the failure to price environmental effects, are rarely addressed. Second, estimates are greatly impacted by the analysis methods used, the scope applied (e.g., timescale, whether state incentives are included), and how different technologies are categorized. Third, estimates are often reported differently, because timescales and units of interest vary. While each of the metrics noted in the table below can be useful depending on the goals of the analysis, the variety of approaches makes it difficult to compare different studies.

Variations in the Types of Incentives Included in Studies	Variations in Methods and Scope	Variations in Metrics Reported
• Direct spending (e.g., grants) • Tax reduction (e.g., tax credits, accelerated depreciation) • Support for R&D • Market access (e.g., access to public land, use mandates) • Risk reduction (e.g., loan guarantees, insurance) • Failure to price environmental effects (rarely included)	• Methods used to assess complicated programs • Scope: generation-only or full life cycle; timescale; treatment of state/local • Whether subsides are allocated to electricity production, and form of categorization into sectors	• Dollar value in recent year ($/year) • Cumulative dollar value since beginning of incentives ($) • Dollar value in first 10–30 years of technology development ($) • Total dollar value in recent year, divided by production (¢/kWh) • Projected future incentives under current policy ($/year)

Text Box 3-3. *(continued)*

Government Incentives for Energy Supply

Complications in Comparing Estimates of Relative Government Incentives

Given these differences, it is difficult to generalize about the relative size of incentives offered to various energy technologies. Depending on the factors included, different studies have reported estimates of total subsidies that vary by more than an order of magnitude (e.g., [52]). In broad terms, however, and focusing principally on federal government incentives since most available studies do not consider state incentives, the literature suggests:

- If "recent incentives per year" is used as the metric, incentives for renewable energy are comparable to—and, in the most recent years (as of 2013), potentially greater than—those provided to nuclear or fossil energy sources; examples from some recent studies are in the table below.
- If "cumulative incentives" or "total incentives over an initial deployment period (10–30 years)" is used as the metric, renewable energy has received fewer incentives relative to nuclear or some fossil energy sources. A 2011 study by DBL Investors, for example, found that, "federal incentives for early fossil fuel production and the nascent nuclear industry were much more robust than the support provided to renewables today" [53]. Studies by the Congressional Research Service [47], Management Information Services [54], the Congressional Budget Office [51], and Badcock and Lenzen [55] present similar results for historical incentive patterns.
- If "recent incentives per unit of electricity" is used as the metric, renewable electricity is more heavily supported than other technologies, in part because renewable energy is still a relatively small share of the overall electricity mix (e.g., [56, 57, 58]).
- If "projected future incentives under current policy" is used, renewable energy sources are sometimes expected to receive relatively lower levels of incentives than other energy sources (e.g., [59]). This is because many of the available federal incentives for renewable energy have expired or are set to expire. In contrast, a number of the currently available incentives for other energy sources do not have an established expiration date.

Virtually none of the studies reviewed consider the failure to fully price environmental impacts as an "incentive." As suggested elsewhere in Chapter 3, however, and as assessed by Kitson et al. [57], the economic consequences of such "externalities" are substantial. If such factors were considered as implicit incentives, a number of the general conclusions herein could change.

Vast differences in approach and findings in the literature make it challenging to draw firm conclusions. It is certain, however, that billions of dollars of incentives are designated for fossil, nuclear, and renewable energy each year and that these diverse incentives have been partly responsible for the development of each sector. The incentives are of many different types, vary significantly from year to year, and are intended to accomplish many different—and sometimes contradictory—purposes. No single, simple answer exists regarding the relative size of these incentives.

Estimates of Recent U.S. Incentives for Various Energy Sources (2013$ billion/year)

Source	GAO 2007	EIA 2008	ELI 2009	EIA 2011	CBO 2012	CRS 2013
Study Period	**2002–2007**	**2007**	**2002–2008**	**2010**	**2011**	**2013**
Nuclear electricity	1.1	1.5	NA	2.7	0.9	NA
Oil and gas	NA	2.4	10.0	3.0	NA	2.7
Coal	NA	3.7	0.5	1.5	NA	0.6
Fossil total[a]	**3.1**	**6.0**	**11.3**	**4.5**	**2.5**	**3.3**
Biofuels	NA	3.6	2.6	7.1	7.0	2.2
Renewables (ex. biofuels)	NA	1.9	1.8	8.5	6.1	11.8
Renewable total[a]	**0.8**	**5.5**	**4.4**	**15.7**	**13.1**	**14.0**

Sources: GAO 2007 [60], EIA 2008 [56], ELI (Adeyeye et al.) 2009 [61], EIA 2011 [58], CBO 2012 [51], CRS 2013 [62].

Note: Table reports average annual incentives in billion dollars per year; values were adjusted from study estimates to 2013$ by multiplying by the annual average Consumer Price Index ratio. NA values are not reported due to different studies using different categorization methods. Caution should be used when comparing these values, as study scope and methods vary substantially, and there were many changes to energy policy in the time period reviewed. Acronyms used in this table: General Accounting Office (GAO); Energy Information Administration (EIA); Environmental Law Institute (ELI); Congressional Budget Office (CBO); Congressional Research Service (CRS)

a. Individual categories do not always sum to total because not all direct spending was reported by fuel.

Continues next page

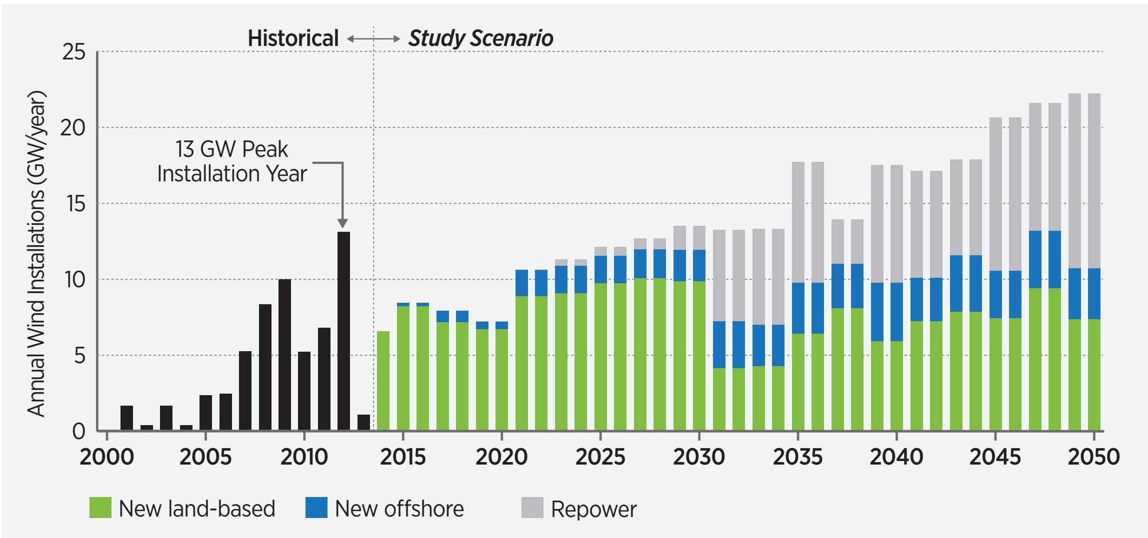
3.3 Wind Capacity Additions and Investment

Moving wind power penetration from approximately 4.5% of end-use demand in 2013 to the *Wind Vision* levels of 10% by 2020, 20% by 2030, and 35% by 2050 is expected to result in changes within the wind energy industry. Among the more notable changes is the anticipated growth in the U.S. wind power fleet. Under the *Wind Vision,* total installed capacity increases from the 61 GW installed at year-end 2013 to ranges of 111–115 GW by 2020, 213–235 GW by 2030, and 382–459 GW by 2050. Results for the *Central Study Scenario* are in the middle of that range, at 113 GW, 224 GW, and 404 GW by 2020, 2030, and 2050, respectively; of this, 3 GW, 22 GW, and 86 GW are from offshore installations in 2020, 2030, and 2050 respectively. This growth requires nearly three doublings of installed capacity. Although capacity and investment levels will vary as a function of technology performance improvements and costs, results presented in this section are primarily based on the *Central Study Scenario*.

3.3.1 Capacity Additions

The *Wind Vision* analysis assumes a linear increase in wind power penetration to the noted levels in 2020, 2030, and 2050. This drives consistent growth in annual capacity additions throughout the period of analysis. Despite continued growth, capacity added in new land-based sites actually declines as technology becomes more productive, deployment of offshore plants increases, and repowering—with its associated performance improvements from installing new equipment—becomes a more substantive share of the annual capacity installations (Figure 3-17).

In the near term, *Central Wind Cost* assumptions result in wind capacity additions of 7.7 GW/year from 2014 to 2020.[54] During this time period, approximately 430 MW/year are offshore and only 1 MW/year is repowered land-based wind facilities. More rapid technological improvements (*Low Wind Costs*) would



Note: New capacity installations include capacity added at a new location to increase the total cumulative installed capacity or to replace retiring capacity elsewhere. Repowered capacity reflects turbine replacements occurring after plants reach their useful lifetime. Wind installations shown here are based on model outcomes for the *Central Study Scenario* and do not represent projected demand for wind capacity. Levels of wind capacity to achieve the penetration trajectory in the *Study Scenario* will be affected by future advancements in wind turbine technology, the quality of the wind resource where projects are located, and market conditions, among other factors.

Figure 3-17. Historical and forward-looking wind power capacity in the *Central Study Scenario*

54. The most recent five-year average of wind capacity additions from 2009 to 2013 is 7.25 GW/year.

Table 3-3. Estimated Average Annual Wind Deployment across Wind Cost Sensitivities

Annual Capacity Additions (GW/year)		2014–2020			2021–2030			2031–2050		
Central Study Scenario	**Total**	**7.7**			**12.1**			**17.5**		
	New Land-Based/New Offshore/Repowered	7.2	0.4	0.0	9.5	1.9	0.7	6.8	3.3	7.4
Low Wind Cost Study Scenario	**Total**	**7.4**			**11.1**			**16.7**		
	New Land-Based/New Offshore/Repowered	6.9	0.4	0.0	8.6	1.8	0.7	6.3	3.2	7.1
High Wind Cost Study Scenario	**Total**	**7.9**			**13.0**			**20.0**		
	New Land-Based/New Offshore/Repowered	7.5	0.4	0.0	10.4	1.9	0.7	9.1	3.4	7.6

Note: Totals may not sum because of rounding.

reduce the average annual new installations for this period to approximately 7.4 GW/year by capturing more energy per unit of installed capacity. Assuming no further technology performance improvements (*High Wind Costs*) increases the annual installed capacity average to 7.9 GW/year but would simultaneously result in increased electric sector costs (see Section 3.6).[55] From 2021 to 2030, growth in the form of annual wind capacity additions increases to 12.1 GW/year in aggregate, with a range of 11.1–13 GW/year again as a function of *Low* and *High Wind Cost* assumptions; approximately 1.9 GW per year are offshore and 0.7 GW/year are repowered land-based wind facilities. From 2031 to 2050, aggregate annual wind capacity additions increase even further to approximately 17.5 GW year (range of 16.7–20 GW/year), with repowering and new offshore installations constituting about 40% and 20% of aggregate annual wind installations, respectively. Table 3-3 summarizes the annual wind deployment results from the *Central Study Scenario, Low Wind Cost,* and *High Wind Cost* sensitivities. Workforce implications associated with these changes in annual capacity additions are detailed in Section 3.11.

3.3.2 Distribution of Capacity

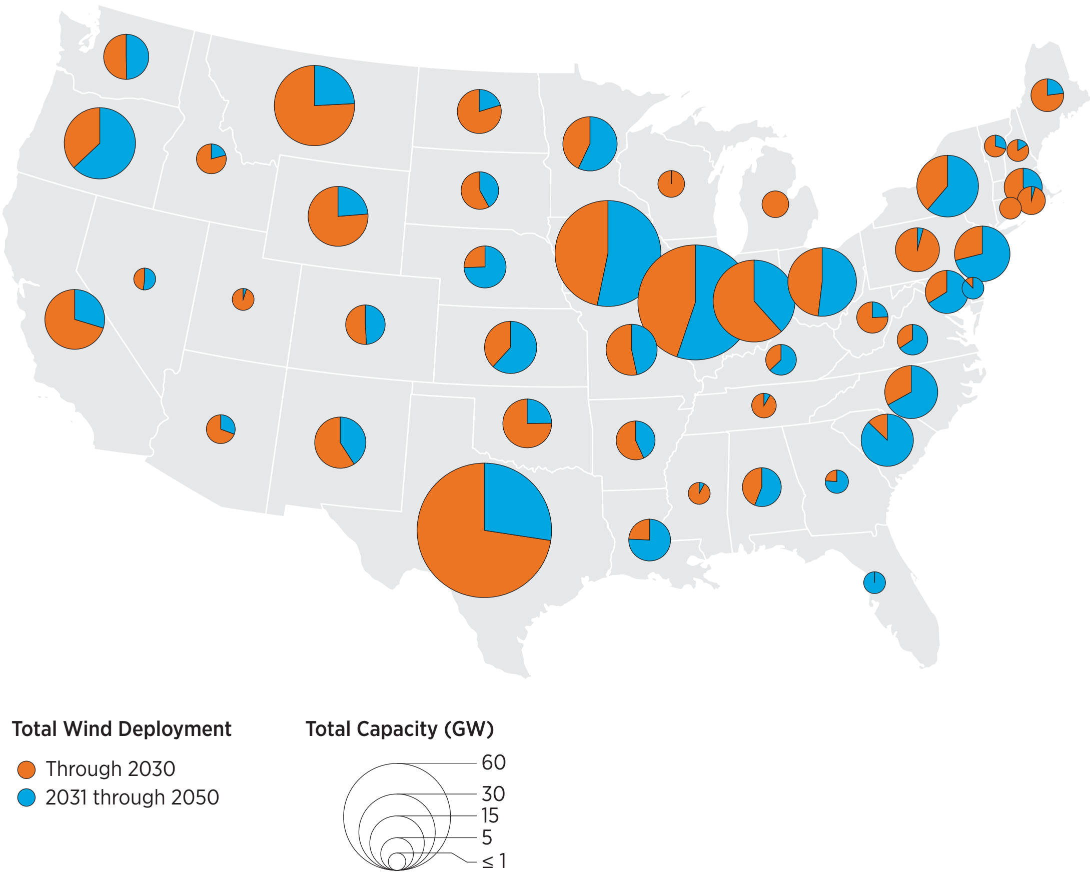
Through year-end 2013, land-based wind power was installed in 39 states; 16 states have more than 1 GW of installed capacity. The *Study Scenario* continues this trend of geographical diversity in wind power. Figure 3-18 illustrates the state-level distribution of wind capacity in 2030 and 2050, as associated with the *Central Study Scenario*.

By 2030, installed wind capacity exists in 49 states, and 37 states have met or surpassed the 1 GW threshold. By 2050, wind deployment is observed in all states and 40 states have more than 1 GW of installed wind capacity.[56]

Although the *Study Scenario* relies on expansion of long-haul transmission lines to move power eastward from the upper Midwest, Great Plains, and Texas, and from the western Interior to the Pacific Coast, the geographic diversity noted earlier is indicative of the fact that technology improvements continue to open previously marginal sites to wind development. Access to lower-quality sites in the Southeast, Northeast, and elsewhere are enabled in part by continued

55. Since the wind electricity penetration levels are prescribed across all *Study Scenarios,* the amount of capacity needed is largely dependent on the assumed capacity factors. As such, the *High Wind Cost Study Scenario* with its associated lower wind capacity factors yields higher installed capacity than the other scenarios.

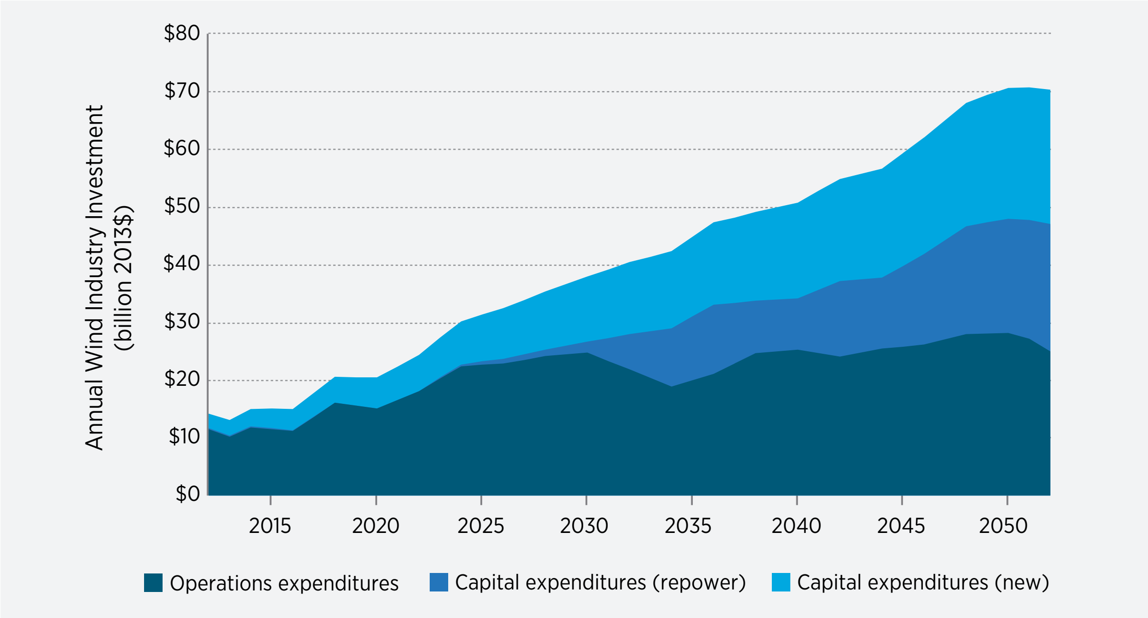
56. As of 2013, wind installations of 62 MW and 206 MW exist in Alaska and Hawaii respectively. While future wind deployment in these states is expected and could potentially grow beyond 1 GW, these states are not counted among the states with more than 1 GW in 2030 or 2050 because the modeling analysis was restricted to the 48 contiguous states.



Note: Results presented are for the *Central Study Scenario*. Across *Study Scenario* sensitivites, deployment by state may vary depending on changes in wind technology, regional fossil fuel prices, and other factors. ReEDS model decision-making reflects a national optimization perspective. Actual distribution of wind capacity will be affected by local, regional, and other factors not fully represented here. Alaska and Hawaii already had wind deployment in 2013. However, future deployment estimates are limited to the 48 contiguous United States due to modeling limitations.

Figure 3-18. *Study Scenario* distribution of wind capacity by state in 2030 and 2050

increases in hub heights and rotor diameters that allow these sites to become economically viable as wind power costs fall, fuel costs increase, and retirements result in more demand for new capacity. In addition, offshore resources offer wind deployment opportunity in regions where land-based resources may be more limited. Land and offshore area impacts associated with the deployment and distribution of wind capacity are discussed in Section 3.12. Transmission expansion impacts of the *Study Scenario* are discussed in Section 3.6.



Note: The value shown for any given year represents a four-year (previous year, year noted, and two future years) rolling average. The capital investments (historical and future) are not amortized.

Figure 3-19. Wind industry investments by market segment in the *Central Study Scenario*

3.3.3 Wind Capital and Operating Expenditures

Annual investment in new wind power plants averaged $15 billion/year from 2009 to 2013. In the *Central Study Scenario,* investments in new plants and ongoing operations average $20 billion/year through 2020 and more than $30 billion/year from 2021 to 2030. Between 2031 and 2050, investment in new plants and operations averages more than $55 billion/year and ultimately grows to more than $70 billion/year by 2050 (constant 2013 dollars).[57] Figure 3-19 illustrates market size by industry segment over time. Consistent with annual capacity additions, growth trends upward throughout the period of analysis despite reduced investments in new sites after 2030. In the long term, repowering and O&M expenditures become significant portions of annual industry expenditures at $22 billion/year and $23 billion/year by 2050, respectively. In fact, repowering and O&M together eventually comprise greater expenditures than new capital investments. Total offshore wind investment (new capacity, repowered capacity, and operations) under the *Central Study Scenario* averages $2.5 billion/year through 2020 before settling at an average of $20 billion/year from 2030 to 2050.

By the mid-2030s, repowering and operations of the fleet provide steady industry demand that is at least partially decoupled from demand for new electric power capacity. This represents a shift from the existing state of the industry, which is largely dependent on new capacity additions to generate capital flow into the industry.

57. The historical capital investment values include the cost of construction financing and some interconnection costs. In contrast, capital expenditures shown for future years simply represent overnight capital investments incurred for each year. These figures exclude construction financing costs, other financing costs, and any interconnection costs.

3.4 Economic Impacts

Impacts to the wind industry are important for direct industry participants. A more holistic view, however, is offered through analysis of the broad-based economic impacts of the *Study Scenario,* along with other costs and benefits provided by wind power. This section describes the estimated economic cost of the *Study Scenario* and associated sensitivities relative to the respective *Baseline Scenario*. Subsequent sections describe the potential benefits and non-economic costs of the *Study Scenario*, which provide context to evaluate the economic impacts presented.

The economic impact of the *Study Scenario* is estimated using two metrics from the ReEDS model—national average electricity price and present value of total system cost—described in Section 3.1.2 and in Short et al. [3]. Both metrics consider all capital and operating expenditures in the U.S. power sector to assess the relative costs of different scenarios.[58] In terms of the limitations of this portion of the analysis, Section 3.1 describes how the system-wide cost optimization perspective of ReEDS might affect the overall cost results of the analysis provided below. None of the economic metrics considered reflects a comprehensive macroeconomic analysis; economic impacts presented in this section are restricted solely to the electricity sector and do not explicitly consider cross-sector interactions, economy-wide impacts, or potential externalities.[59] The economic impact is assessed for the continental United States as a whole and distributional effects are not presented. Regional economic impacts will depend on future markets and regulations that are beyond the scope of the present analysis.

Notwithstanding these limitations, the electricity price and system cost impacts provide insights into the magnitude and direction of economic impacts associated with the *Study Scenario*.

3.4.1 National Average Retail Electricity Price Impacts

The *Wind Vision* analysis shows that, for the near-term (2020) and mid-term (2030), electricity price differences between the *Central Study Scenario* and the *Baseline Scenario* have a (positive) incremental cost of less than 1% (Figure 3-20 and Table 3-4). In the long-term (2050), electricity price *savings* exist for the *Central Study Scenario,* driven primarily by reduced wind costs and increased fossil fuel costs. Higher near-term incremental costs and reduced long-term savings are possible if fossil fuel costs are lower and/or wind technologies realize less improvement than estimated in the *Central* assumptions. Conversely, incremental costs can be reduced or eliminated through some combination of higher fossil fuel costs or greater wind cost improvements.

Estimated electricity prices presented in this section represent national average retail prices to serve the average consumer across regions and sectors—industrial, residential, and commercial. Figure 3-20 shows estimated price trajectories for the full array of *Study Scenario* and *Baseline Scenario* sensitivities. Before 2030, for the *Central Study Scenario* (and respective *Baseline Scenario*) estimated average electricity prices remain similar to recent historical prices for both scenarios; prices increase about 0.3¢/kWh from 2013 to 2030.[60] The relatively flat electricity price trajectories during this time period reflect, in part, the limited need for new capacity in the near term (Section 3.2.4). Beyond 2030, electricity prices in both the *Study Scenario* and the *Baseline Scenario* increase more rapidly due to rising fossil fuel costs and the increase in demand for new capacity driven by load growth and retirements. Retail electricity

58. The ReEDS model represents the expansion and dispatch of the bulk transmission-level electric system, but does not model the distribution system. As such, expenditures for the distribution network are not captured in the cost estimates. In addition, while the cost of transmission expansion is considered, the cost to maintain the existing transmission network is not. Finally, while retirements are based on assumed plant lifetimes that exceed many decades (see Section 3.2.4 for technology-specific retirement assumptions), refurbishment costs beyond standard O&M are not included. As the economic impact of the *Study Scenario* is assessed relative to the reference *Baseline Scenario,* many of these limitations have little effect on the incremental cost impacts. Future expenditures for the distribution system, transmission maintenance, and plant refurbishment would exist at similar levels across the *Study Scenario* and *Baseline Scenario,* and their omission therefore has limited impact on the estimated incremental costs.

59. Section 3.10 describes the impacts of the *Study Scenario* on fuel diversity and price suppression effects that extend beyond the power sector. Section 3.11 describes national impacts on workforce and economic development, and Section 3.12 discusses local impacts.

60. All costs are presented in real 2013$ throughout this section and chapter unless otherwise noted. As such, any estimated price increases reflect increases above inflation.

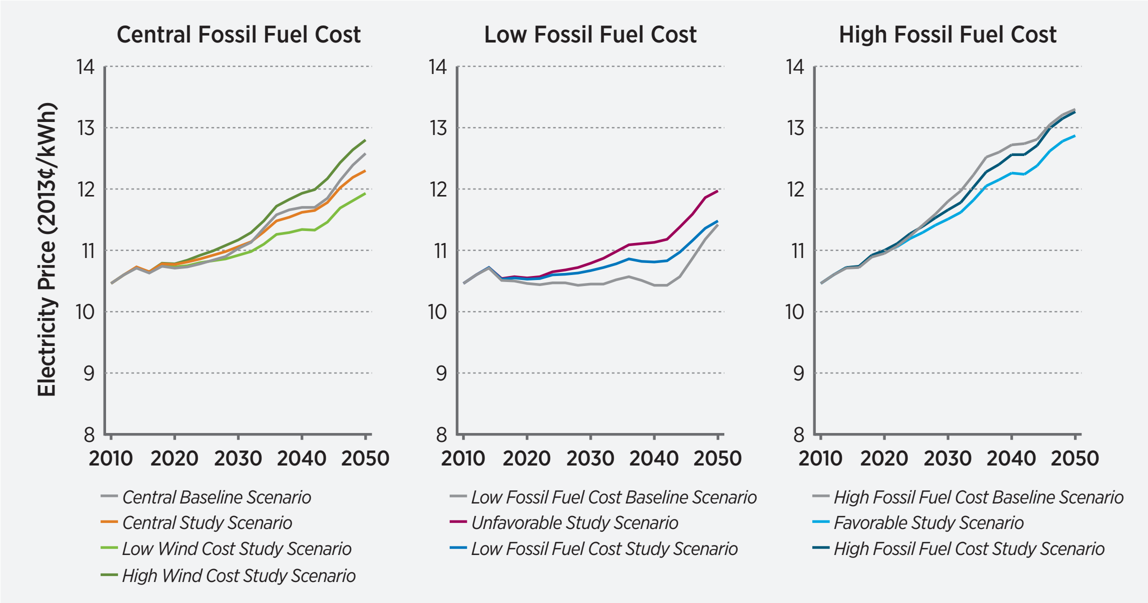


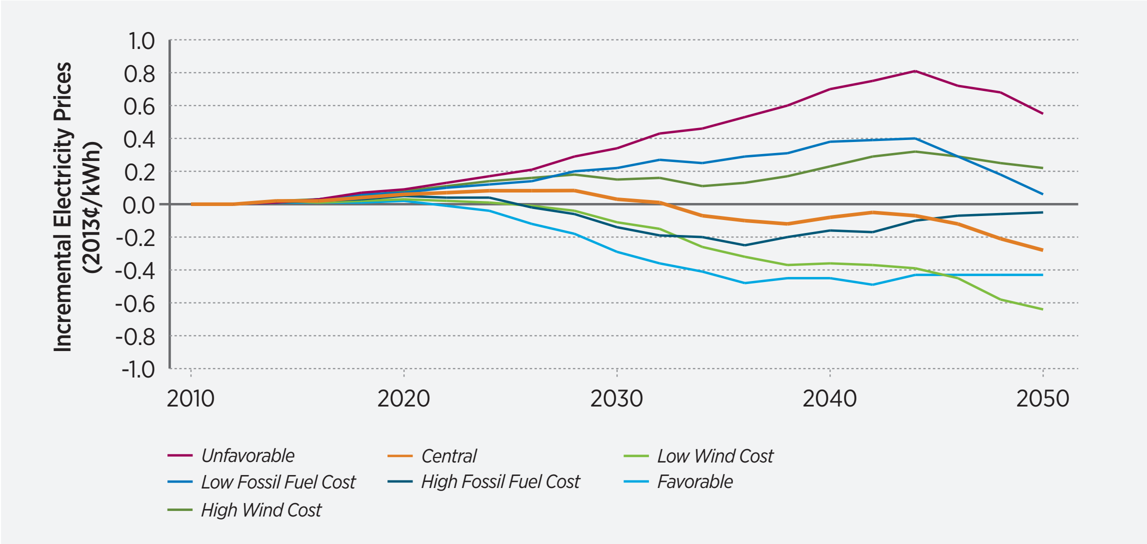
Figure 3-20. National average retail electricity price trajectories for the *Study Scenario* and *Baseline Scenario* (across sensitivities)

prices in 2050 are estimated to be 12.6¢/kWh and 12.3¢/kWh for the *Central Baseline Scenario* and *Study Scenario*, respectively. Uncertainties exist for all estimates and increase with time.

Study Scenarios with higher and lower wind technology cost projections, but still under *Central Fuel Cost* assumptions, yield 2050 electricity prices of 12.8¢/kWh and 11.9¢/kWh, respectively. Under *Low Fuel Cost* assumptions, electricity prices are generally flat through 2040 for the *Study Scenario* and experience a slight decline for the *Baseline Scenario* over the same period of time. From 2040 to 2050, electricity prices in both the *Baseline Scenario* and *Study Scenario* experience a sharper increase, however, 2050 prices remain lower (at 11.4-11.5¢ /kWh) than all scenarios under *Central Fuel Cost* assumptions. The *Unfavorable* (combined *Low Fuel Cost* and *High Wind Cost*) *Study Scenario* results in electricity prices that are higher than the other *Low Fuel Cost* scenarios. Under *High Fuel Cost* assumptions, electricity prices rise more rapidly and result in 2050 prices of about 13.3¢/kWh for both the *Baseline Scenario* and *Study Scenario*. *Favorable* (combined *High Fuel Cost* and *Low Wind Cost*) conditions yield lower prices for the *Study Scenario*, but the 2050 price in this scenario remains higher than prices under all scenarios under *Central* or *Low Fuel Cost* conditions. These results point to the influence of future fuel prices on electricity rates.

While future fuel prices will impact the magnitude of electricity prices across any scenario, they—along with future wind technology development—also impact the incremental price of achieving the *Study Scenario* relative to the *Baseline Scenario*. Figure 3-21 shows the incremental electricity price across all modeled *Study Scenario* sensitivities, where the incremental price is defined as the difference in electricity price between the *Study Scenario* and the corresponding base fuel price *Baseline Scenario* sensitivity.[61] In 2020, the incremental electricity price is 0.06¢/kWh (+0.6%) for the *Central Study Scenario*. The range of electricity price impacts reflect 2020 incremental *costs* of up to about 0.09¢/kWh (+0.9%) under the least favorable conditions considered—*High Wind Cost* and *Low Wind Cost*. Under favorable conditions, incremental costs are only 0.02¢/MWh (+0.2%). While the near-term incremental electricity prices of the *Study Scenario* sensitivities depends on future wind technology cost and future fuel prices, the magnitude of the 2020 electricity price impacts is relatively small across all sensitivities considered.

61. The *Central, High Wind,* and *Low Wind Study Scenario* sensitivities are compared with the *Central Baseline Scenario;* the *High Fuel Cost* and *Favorable Study Scenario* sensitivities are compared with the *High Fuel Cost Baseline Scenario;* and the *Low Fuel Cost* and *Unfavorable Study Scenario* sensitivities are compared with the *Low Fuel Cost Baseline Scenario.*



Note: Incremental prices are shown relative to the associated fuel cost *Baseline Scenarios* in which installed wind capacity is fixed at 2013 levels.

Figure 3-21. Incremental average electricity prices in *Study Scenario* sensitivities relative to the *Baseline Scenario*

The incremental electricity price of the *Central Study Scenario* is positive between 2020 and 2030 (representing a *cost* relative to the *Baseline Scenario*), peaking at 0.08¢/kWh (+0.8%) in the mid-2020s. By 2030, this incremental price drops to 0.03¢/kWh (+0.3%). The range of estimated incremental prices across all sensitivities modeled is larger in 2030 than in 2020, with an incremental *cost* of up to 0.34¢/kWh (+3.3%) and *savings* of up to 0.29¢/kWh (–2.4%). Future fossil fuel costs and advances in wind technology are found to have measurable effects on 2030 incremental prices with the directionality following the expected manner: Low wind costs, high fuel costs, or their combination lead to incremental savings; while high wind costs, low fuel costs, or their combination lead to incremental costs.

For the *Central Study Scenario*, the 2050 electricity price is estimated to be 0.28¢/kWh (–2.2%) lower than the *Baseline Scenario*. In fact, incremental savings in electricity prices are found across a majority of *Study Scenario* sensitivities. Wind technology improvement provides the greatest long-term savings; the largest 2050 price savings are about 0.64¢/kWh (-5.1%) in the *Low Wind Cost* sensitivity, while the *Favorable* sensitivity achieves savings of 0.43¢/kWh (–3.2%).[62] Greatest 2050 incremental costs of 0.55 cents/kWh (+4.8%) are found in the *Unfavorable* sensitivity.[63] While uncertainty exists for cost estimates during this time period, the analysis indicates that, in the long term, deployment of wind power to reach levels in the *Study Scenario* is cost effective under a range of possible future conditions, including under *Central* assumptions.

The estimated average retail rate impacts can be translated to annual electricity consumer impacts by evaluating the product of the incremental prices above with projected end-use electricity demand. Incremental annual electricity consumer *costs* for the *Central Study Scenario* total $2.3 billion and $1.5 billion in 2020 and 2030, respectively. In 2050, electricity consumers are estimated to *save* $14 billion in the *Central Study Scenario* relative to the *Baseline Scenario*. The range of incremental annual electricity consumer 2020 *costs*—across all sensitivities—is $0.8–$3.6 billion. By 2030, annual incremental *costs* grow to up to $15 billion under the least favorable conditions, but *savings* of $12 billion are estimated to be possible under favorable ones. Consumer impacts in 2050 range from possible *savings* up to $31 billion to *costs* of up to $27 billion.

62. The *Low Wind Cost Study Scenario* sensitivity counterintuitively achieved slightly greater 2050 savings than the *Favorable* sensitivity. Two separate *Baseline Scenarios* are used as references, however, to estimate incremental prices for these *Study Scenario* sensitivities. As such, the greater savings found under the *Low Wind Cost* sensitivity is possible. The difference in 2050 incremental prices between these scenarios is small.

63. Under the *Unfavorable* sensitivity, peak incremental prices occur in the mid-2040s, at about 0.81¢/kWh (+7.6%).

Table 3-4. Changes in Electricity Prices for the *Study Scenario* Relative to the *Baseline Scenario* (Across Sensitivities)

	2020	2030	2050
Central Study Scenario electricity price (change from *Baseline Scenario*)	0.06¢/kWh cost (+0.6%)	0.03¢/kWh cost (+0.3%)	0.28¢/kWh savings (-2.2%)
Central Study Scenario annual electricity consumer costs (change from *Baseline Scenario*)	$2.3 billion costs	$1.5 billion costs	$13.7 billion savings
Study Scenario sensitivity range (% change from *Baseline Scenario*)	+0.2% to +0.9%	-2.4% to +3.2%	-5.1% to +4.8%
Study Scenario annual electricity consumer costs range (change from *Baseline Scenario*)	$0.8 to $3.6 billion costs	$12.3 billion savings to $14.6 billion costs	$31.5 billion savings to $26.9 billion costs

Note: Expenditures in 2013$

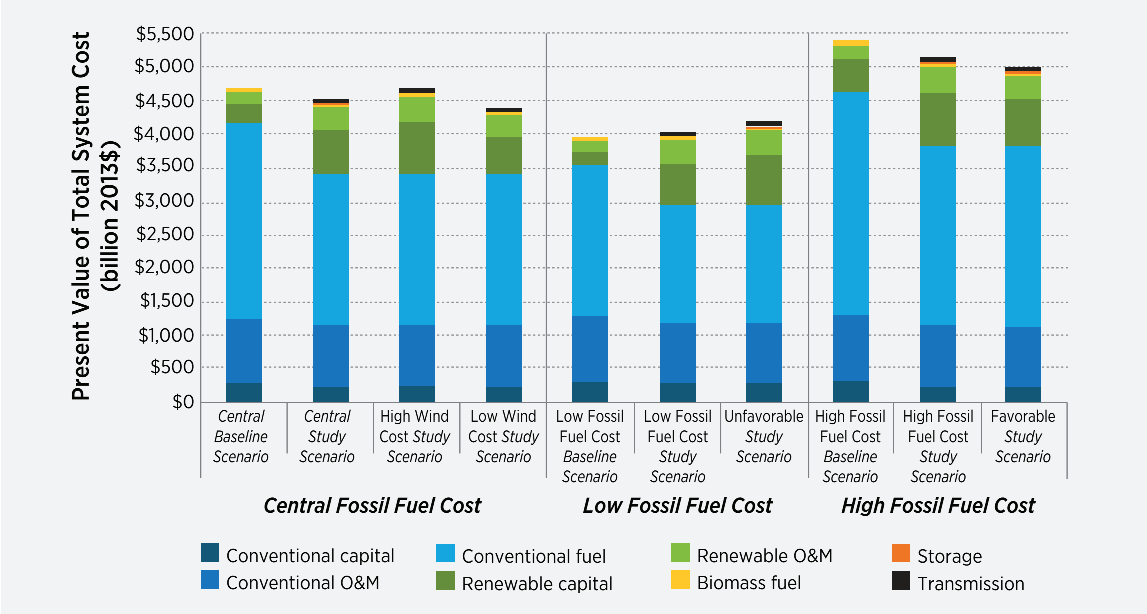
3.4.2 Present Value of Total System Cost

The present value of total system cost measures cumulative expenditures over the entire study period (2013-2050). Figure 3-22 shows the present value of total system costs for all *Baseline* and *Study Scenario* sensitivities modeled with a 3% real discount rate.[64] Multiple cost components are shown separately in Figure 3-22, including capital, O&M, and fuel costs for conventional and renewable technologies.[65] Under the *Central Baseline Scenario*, system costs total approximately $4,690 billion. A large fraction (62%) of this cost is for conventional fuel—coal, natural gas, uranium—expenditures. With conventional fuel expenditures greatly outweighing any other cost category under the *Baseline Scenario* conditions, future fuel price assumptions have a dramatic effect on total system costs. For example, under the *High Fuel Cost Baseline Scenario*, the present value of total system cost equals $5,390 billion, 15% higher than the *Central Baseline Scenario*. Conversely, under the *Low Fuel Cost Baseline Scenario*, present value of total system cost totals $3,940 billion, 16% lower than the *Central Baseline Scenario*.

The *Central Study Scenario* is found to have a present value of total system cost of nearly $4,540 billion, 3% lower (–$149 billion) than that of the *Baseline Scenario*. These results and the electricity price results presented earlier indicate that the long-term *savings* of the *Central Study Scenario* outweigh the near-term incremental *costs* relative to the *Baseline Scenario* in which no wind capacity is deployed after 2013, even after accounting for the greater discount factor in the long term. The majority of the savings are associated with decreased conventional fuel expenditures (–$670 billion) at the expense of increased renewable capital (+$380 billion) and renewable O&M (+$170 billion) expenditures. The *Study Scenario* results with higher and lower wind technology cost have respective higher and lower total system cost than the *Central Study Scenario*. Different assumed fuel price trajectories have a similar effect on the total system cost of *Study Scenario* sensitivities as on the *Baseline Scenario* sensitivities. The range of system costs driven by fossil fuel assumptions, however, is narrower under *Study Scenario* sensitivities versus the *Baseline Scenario* sensitivities. This narrowing is a function of

64. The discount rate used in ReEDS (8.9% nominal or 6.2% real) is not to be confused with the discount rate used to describe the present value of overall system cost (5.6% nominal or 3% real). The discount rate used in ReEDS is selected to represent private-sector investment decisions for electric system infrastructure and approximates the expected market rate of return of investors. The lower "social" discount rate is only used to present the cost implications of the *Wind Vision Study Scenario* results and is generally consistent with the discount rate used by the DOE, EIA, International Energy Agency, and Intergovernmental Panel on Climate Change when evaluating energy technologies or alternative energy futures. A 3% discount rate is also consistent with The White House Office of Management and Budget guidance when conducting "cost-effectiveness" analysis that spans a time horizon of 30 years or more.

65. Conventional technologies include fossil (coal, natural gas, oil) and nuclear generators. Renewable technologies include wind (land-based and offshore), biomass (dedicated and co-fired with coal), geothermal, hydropower, and solar (utility-scale PV and concentrating solar power). Expenditures associated with distributed rooftop PV are not considered in the total system costs. This omission has no effect on incremental costs, as the same rooftop PV capacity projections are used across all *Baseline* and *Study Scenario* sensitivities.



Note: Present value of total system costs for 2013-2050 calculated using a 3% discount rate

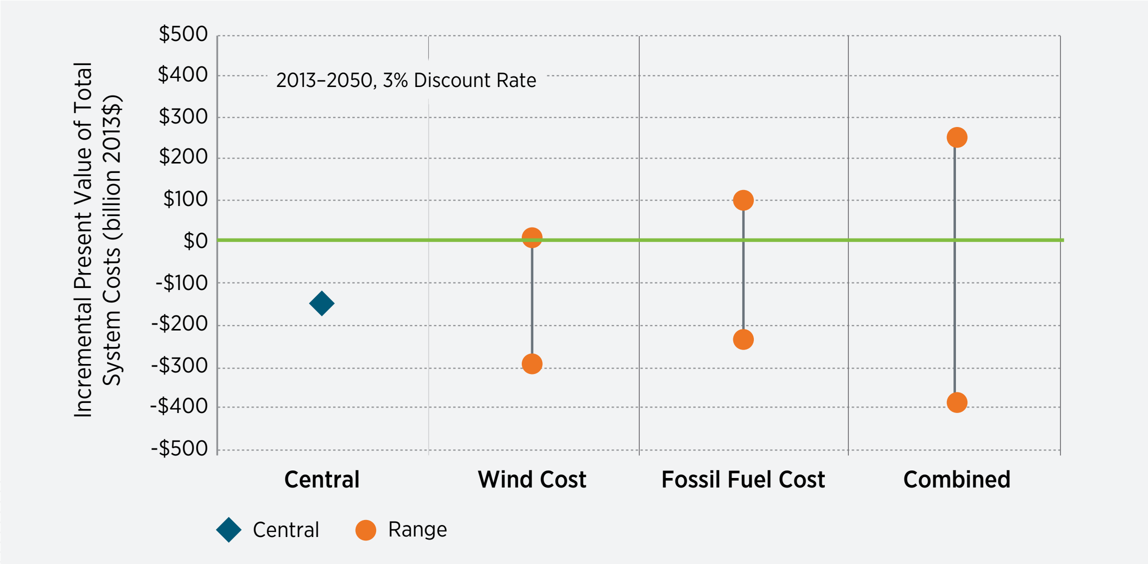
Figure 3-22. Present value of total system cost for the *Baseline Scenario* and *Study Scenario* (across sensitivities)

the reduced prominence of fossil fuel in the cumulative portfolio and is discussed in greater detail in Sections 3.5 and 3.10.

Figure 3-23 shows the incremental total system cost for the *Study Scenario* sensitivities relative to the corresponding *Baseline Scenario* sensitivities. The *Central Study Scenario* is estimated to have a system cost that is $149 billion lower (–3%) than that of the *Central Baseline Scenario*. Greatest savings are observed under the *Favorable Scenario* (combined low wind power and high fossil fuel costs), in which the total system cost is $388 billion lower (–7%) than that of the *High Fuel Cost Baseline Scenario*. In contrast, the greatest incremental present value of total system cost is observed under the *Unfavorable Scenario* (combined high wind power costs and low fossil fuel costs), in which an incremental cost of $254 billion (+6%) relative to that of the *Low Fuel Cost Baseline Scenario* is estimated.[66]

In summary, the incremental economic impacts of the *Study Scenario* sensitivities ranges from a *savings* of up to 7% to a *cost* of up to 6%, in present value terms (2013–2050, 3% discount rate). The results indicate that—while fossil fuel prices are important drivers for these incremental costs—wind technology improvements can help reduce the cost to achieve the *Wind Vision* penetration levels or even enable savings compared with a future in which no new wind capacity is placed in service. *Central* assumptions of wind costs and fuel prices result in savings of $149 billion (–3%). This demonstrates the economic competitiveness of wind despite low fossil fuel prices in years leading up to 2013, particularly when economic impacts are evaluated over multiple decades.

66. Using a higher discount rate would lead to lower overall system costs for both *Baseline Scenario* and *Study Scenario* sensitivities, and changes in incremental costs. For example, with a 6% (real) discount rate, present value of system cost for the *Central Baseline Scenario* and *Study Scenario* is estimated to be nearly identical. On a percentage basis, the upper range of incremental costs would increase to about 8% (+$212 billion), while the possible magnitude of percent savings would decline to about 5% (–$173 billion). These changes related to a higher discount rate reflect the changing competitiveness of wind relative to other technology options over time, under the assumptions used.



Note: Ranges reflect the incremental prices for the *Study Scenario* relative to the comparable *Baseline Scenario.* Categories of results reflect the specific sensitivities considered. *"Wind Cost"* reflects the change in impact across the *Low Wind Cost* and *High Wind Cost Scenarios, "Fossil Fuel Cost"* reflects the change in impact across *High Fossil Fuel Cost* and *Low Fossil Fuel Cost Scenarios,* and "Combined" refers to the change in impact across the *Favorable* and *Unfavorable Scenarios* in which low wind costs are combined with high fossil fuel costs and high wind costs are combined with low fossil fuel costs, respectively.

Figure 3-23. Incremental system costs of *Study Scenario* sensitivities relative to the *Baseline Scenario*

3.5 Electricity Sector Impacts

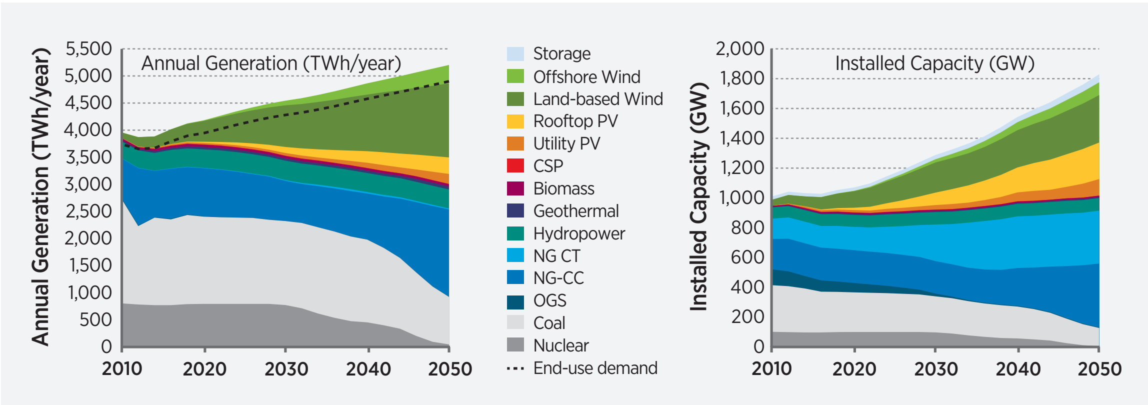
Electricity generated in the United States in 2013 totaled approximately 4,058 TWh. Of this, coal-fired generation comprised the largest share at 39%, followed by natural gas-fired generation at 28%.[67] Nuclear and hydropower power plants contributed 19% and 6.6%, respectively. Generation from wind power plants totaled 4.1% of 2013 generation.[68] Other renewable technologies, including solar, geothermal, and biomass, contributed 2.1%.[69] Among seven broad technology categories—coal, natural gas, nuclear, hydropower, wind, solar, and other renewable energy—wind was the fifth largest contributor to the U.S. electricity system on a net electricity generation basis. Wind electricity was generated from approximately 61 GW of installed wind capacity by year-end 2013. There are approximately 941 GW in total installed capacity in the 2013 U.S. electricity generation fleet.

This section describes the evolution of the U.S. electric system from the 2013 starting point envisioned under the *Study Scenario* and *Baseline Scenario*. This discussion includes description and illustration of the generation and capacity mixes under the scenarios.

67. The total market share from fossil fuel-fired generation has not changed significantly in the decade leading up to 2014. Significant fuel switching from coal to natural gas has been observed since 2010, however, primarily driven by historically low natural gas prices from 2010 to 2013.

68. The wind generation share (4.1%) presented here differs from the percentage of end-use demand (4.5%) indicated elsewhere in the report, but both reflect the same amount of electricity produced from wind power plants.

69. Values for 2013 are taken from the EIA electric power monthly (*www.eia.gov/electricity/monthly*). Reported natural gas generation values here and throughout this section include oil-fired steam generators. Hydropower generation values include electricity produced by domestic hydropower plants only—excluding net generation from pumped hydropower storage. The scenario results presented include net imports from Canada, which the Canadian National Energy Board notes totaled 42 TWh in 2013 and are assumed to be 34–52 TWh annually in future years. Solar generation represents all grid-connected solar facilities, including utility-scale concentrating solar power and PV, and distributed PV.



Note: Total generation exceeds end-use demand due to transmission and distribution losses. Technology category acronyms: PV = photovoltaic, CSP = concentrating solar power (with and without thermal energy storage), NGCT = natural gas-fired combustion turbines, NGCC = natural gas-fired combined cycle, OGS = oil and gas steam turbines. Biomass includes dedicated biopower, co-fired biomass with coal, and landfill gas or municipal solid waste capacity; hydropower includes all net Canadian imports.

Figure 3-24. Annual generation and installed capacity by technology type and year under the *Central Study Scenario*

The position of wind power within this broader electric sector is provided here for context, while Section 3.3 more fully describes the impacts to the wind industry specifically.

Significant uncertainty exists for all time periods, and an even greater degree of uncertainty exists in the long term. Uncertain factors that can and will drive future investment and dispatch decisions in the electric system include environmental regulations, electricity demand growth and plant retirements (particularly coal and nuclear retirements), and future technology and fuel costs. While results from scenario variations of two key drivers—wind power costs and fossil fuel costs—are described to provide an indication of the range of possible outcomes, these and other uncertainties need to be recognized in interpreting scenario results. Also, none of the scenarios represent forecasts or projections.

3.5.1 Evolution of the Electricity Sector under the *Study Scenario*

In the wind penetration levels of the *Study Scenario*, total wind power generation moves from its 2013 position as the fifth largest source of annual electricity generation to the second largest source of electricity by 2030, and to the single largest source of electricity generation by 2050 in the *Central Study Scenario*.

Growth in electricity demand through 2030 is met primarily by the expansion of wind under the *Study Scenario*. Figure 3-24 shows the generation and capacity mixes under the *Central Study Scenario*. As shown, the growth in wind generation exceeds the growth in electricity demand for most years, reducing aggregate generation from other energy sources. Reductions in fossil fuel-based generation on absolute and percentage bases are observed. Under the *Central Study Scenario*, fossil fuel-based generation comprises about 64% and 54% of end-use demand in 2020 and 2030, respectively, compared to about 70% in 2013. While annual electricity generated from non-wind renewable and nuclear technologies does not exhibit a similar decline by 2030, its growth is limited under the *Study Scenario*. Outside of wind, solar generation exhibits the greatest growth, at 1% in 2020 to 4% in 2030, although from a smaller starting base. Nuclear generation remains generally constant (18%–20%) through 2030, as the current nuclear fleet continues to operate through its assumed first service life extension period. Other technologies experience changes in annual generation on the order of tens of TWh or less.[70] For example, hydropower generation remains at 8–9% of end-use demand through 2030, including imports from Canada.

70. Percentage totals for the *Central Study Scenario* or any other single scenario exceed 100% because the percentages reflect the fraction of end-use demand and not total generation. Transmission and distribution losses total 6–7% of total generation.

From 2030 to 2050, assumed retirements combined with load growth begin to have a more dramatic effect on the generation mix. During this time period, growth in wind generation under the *Study Scenario* continues to exceed growth in electricity demand. By 2050, natural gas-fired generation in the *Central Study Scenario* equals 33% of end-use demand, representing higher absolute natural gas-fired generation than historical totals. Along with wind generation, natural gas replaces declining coal and nuclear generation. In 2050, coal generation makes up only 18% of end-use demand, and nuclear comprises less than 1% in the *Central Study Scenario*.[71] Growth in solar generation continues relatively steadily and reaches about 10% in 2050. Hydropower and other renewable energy generation remain largely at current levels, making up 7% and 2% of total 2050 end-use demand, respectively.

Under the *Central Study Scenario*, the *capacity* expansion trajectory (Figure 3-24, right) largely follows the same trends as the *generation* trajectory (Figure 3-24, left) with three important differences. First, while coal generation is observed to hold relatively steady in the near term, coal capacity actually declines by about 66 GW between 2013 and 2030. Second, while oil and gas steam capacity also declines over this time period, growth in natural gas combustion turbine capacity more than makes up for this decrease. These natural gas units provide peaking and reserve capacity needs and, thus, play an important role for the U.S. power sector that is not observed in the annual generation values presented earlier. Third, the rate of growth in installed capacity is observed to be higher than the rate of growth in annual generation, primarily as a result of rapid growth in wind and solar PV capacity. Wind and solar PV have a lower capacity factor compared with many other energy sources (e.g., nuclear and coal) that are being replaced in the long term. Among the non-wind renewable technologies, solar technologies exhibit the greatest capacity increases, reaching 33 GW by 2020, 116 GW by 2030, and 357 GW by 2050. Capacity growth is limited for other renewable technologies.[72]

In summary, under the *Study Scenario,* the U.S. electricity sector experiences a significant transformation. In the near term, the growth of wind power satisfies new electricity demand and replaces declining fossil generation. In the long term, significant declines in coal and nuclear are observed and replaced by the continued growth of wind, solar, and natural gas generation.

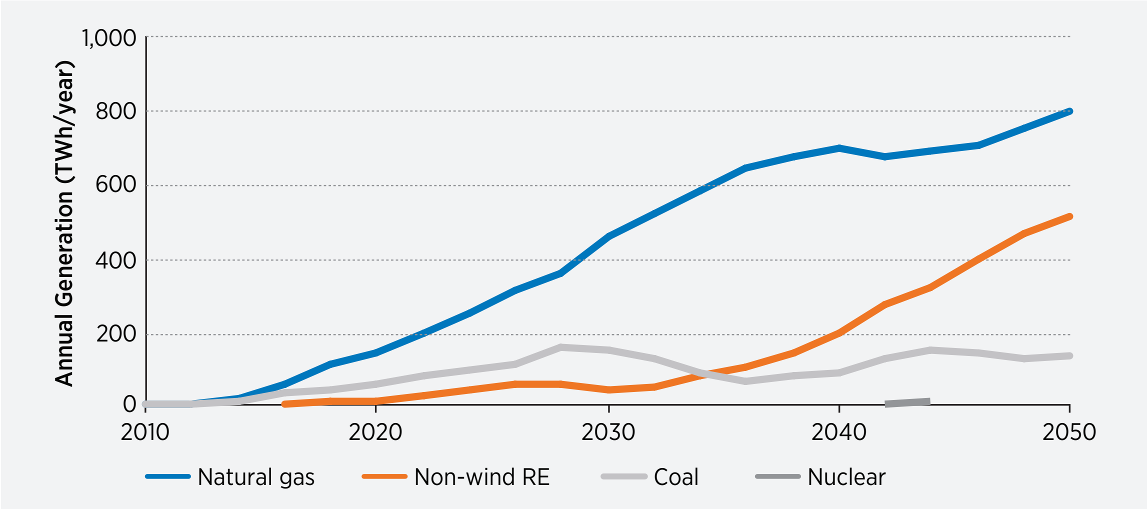
3.5.2 Comparing the Electric Sector under the *Study Scenario* and *Baseline Scenario*

The *Baseline Scenario* sensitivities provide the requisite reference scenario needed to evaluate the costs and benefits of the *Study Scenario* sensitivities. The change in generation between these two scenarios under central assumptions drives many of the environmental and other impacts reported in Sections 3.7-3.12.

Figure 3-25 shows the difference in non-wind generation between the *Central Baseline Scenario* and *Study Scenario* for four categories: natural gas, coal, nuclear, and non-wind renewable generation. The difference in non-wind generation reflects the type of generation "displaced" by wind between these two scenarios. In the near- and mid-term, wind generation primarily displaces fossil generation. In particular, 2020 wind generation under the *Central Study Scenario* primarily takes the place of fossil generation found in the *Baseline Scenario*, including 142 TWh of natural gas-fired generation and 54 TWh of coal-fired generation. Wind continues to displace fossil generation in 2030, including 452 and 149 TWh of natural gas-fired and coal-fired generation, respectively. Differences in generation shares in the other broad technology

71. In the modeled scenarios, nuclear and coal generation is largely driven by assumptions around the available installed capacity of these plants, due to the low operating costs of nuclear and many coal-fired plants. Nuclear units are assumed to be retired after one service life extension period, resulting in a 60-year lifetime for nuclear units. With a second service life extension and the associated total 80-year lifetime, nuclear would achieve greater generation in the latter years than the findings suggestion. Other plant retirement assumptions are described in Section 3.2.4 and Appendix G.

72. Section 3.2.2 describes the underlying assumptions used for this analysis. While technology sensitivities beyond wind power costs were not conducted as part of this study, they would yield different results. For example, the inclusion of other geothermal technologies with greater resource potential—including undiscovered hydrothermal and greenfield-enhanced geothermal systems—could lead to greater market share from geothermal generation. Different assumptions about hydropower, such as inclusion of upgrades at existing facilities or new sites with <1 MW capacity, biomass costs and resources, or nuclear technology costs, could also yield larger shares from these energy sources.



Note: The positive values indicate there was greater generation from these sources under the *Baseline Scenario* compared with the *Study Scenario*. The "natural gas" category includes oil-fired generation. Non-wind RE refers to non-wind renewable energy.

Figure 3-25. Difference in annual generation between the *Central Study Scenario* and *Baseline Scenario* by technology type

categories are more modest through 2030. For example, in aggregate, 42 TWh of all non-wind renewable technologies are displaced by wind in 2030.

Wind deployment under the *Central Study Scenario* continues to displace fossil generation in the long term, including 789 TWh of displaced natural gas-fired generation and 130 TWh of displaced coal displacement in 2050. The growth in the displacement of natural gas and more constant amount of coal displacement reflects the underlying fossil fuel switching observed in both the *Study Scenario* and *Baseline Scenario*. With an electric sector transitioning over time to be more heavily dependent on natural gas compared to coal, the *Central Study Scenario* results in greater amounts of avoided natural gas in the long term. By 2050, wind not only displaces fossil generation, but also has a significant impact on solar generation; the *Central Study Scenario* includes 489 TWh less solar generation in 2050 than the *Baseline Scenario*. Differences in 2050 hydropower and other renewable energy generation are smaller, at 18 TWh in total. Under *Central* assumptions, differences in nuclear generation between the *Baseline Scenario* and *Study Scenario* results are negligible in all years.

The amount of capacity displaced is not as drastic as the amount of electricity production displacement, particularly for the near- and mid-terms. The *Central Study Scenario* results in minor reductions of natural gas-fired combustion turbine capacity (5 GW) in 2020 compared with the *Baseline Scenario*. In 2030, these differences grow to 22 GW of natural gas combustion turbine and also include 5–6 GW each of natural gas-fired combined cycle and coal capacity. Even by 2050, differences in installed fossil capacity between these two scenarios remain relatively small at 51 GW and 14 GW, respectively, of natural gas and coal, compared with a fleet of about 1,800 GW.[73] The much smaller displacement of fossil capacity compared to fossil generation by the *Study Scenario* reflects some of the system-wide contributions the fossil fleet provides beyond energy provision, as described in Sections 2.7 and 3.6.

73. The *Central Study Scenario* includes greater natural gas-fired combustion turbines capacity (+43 GW) compared with the *Central Baseline Scenario,* but less natural gas-fired combined cycle capacity (-94 GW), resulting in a net difference of only 51 GW of 2050 natural gas capacity. This trade-off reflects wind's greater role in providing energy compared with capacity reserves.

3.5.3 The Evolution of the Electricity Sector is Dependent on Future Fuel Prices

Assumptions around fossil fuel prices can have a sizable effect on the evolution of the electricity system, particularly on the generation differences found across the full set of *Baseline* and *Study Scenario* sensitivities. While three variants of wind technology cost scenarios are modeled, future wind technology development is found to have little effect on the remaining generation mix under the prescribed scenario framework.[74] For all years up to 2030, different fuel price assumptions largely affect the relative displacement of natural gas and coal-based generation, indicating the fuel switching possibility between coal and natural gas in the U.S. electricity system.[75] By 2050, the direct trade-off between coal and natural gas is reduced relative to earlier years, but the contributions from natural gas remain strongly tied to assumed long-term fuel prices. For example, in 2050, natural gas generation reaches 62% of 2050 end-use demand (from more than 3,000 TWh) under the *Low Fuel Cost Baseline Scenario* compared with 32% under the *High Fuel Cost Baseline Scenario.* During this long-term period, the trade-off is made between natural gas and other technologies, primarily nuclear and non-wind renewables.[76]

Under the scenario construction of this study, wind generation levels over time are prescribed. As a consequence, other generation sources will achieve less generation in the *Study Scenario* compared to the corresponding *Baseline Scenario*. The starkest differences are found in 2050, when the 35% wind penetration displaces fossil generation and leaves less room for nuclear and renewable generation. The mix of displaced generation enables a consistent estimate of the impacts, costs, and benefits of future wind deployment. Ultimately, however, the generation mix will depend on economic, policy, and other conditions—including those that can accommodate growth of multiple technology types.

3.6 Transmission and Integration Impacts

The primary role of electric system operators and planners is to ensure reliable delivery of electricity at the lowest cost to meet demand. Challenges in serving this role result from variability and uncertainty that exists in the electric power system at all timescales—from multiple decades to microseconds. Variability and uncertainty are inherent in the system as a result of changing electricity demand and generator availability, as well as the potential for power plant and transmission line outages. Although sources of variability and uncertainty exist throughout the power system, including from all generator types, greater reliance on variable output generation such as wind further add to the challenges of system operation. Increasing penetration[77] of wind energy may result in increased ramping needs, increased operating reserves, and transmission expansion. Section 2.7 provides a description of the renewable integration challenges and solutions experienced recent to 2013. This section (3.6) presents the ReEDS scenario results associated with transmission expansion and grid integration and does so within the context of broader transmission and grid integration issues with increased renewable penetration.

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74. Wind technology costs have a more sizable effect on the cost implications of the *Study Scenario*, as described in Section 3.4.

75. The *Low Fuel* and *High Fuel Cost* scenarios assume both coal and natural gas fuel prices to be adjusted in the same direction relative to the *Central* assumption; however, the scenario assumptions change the relative competitiveness of these two energy sources.

76. Installed 2050 nuclear capacity totals about 83 GW under the *High Fuel Cost Baseline Scenario* compared with about 6–16 GW in all other scenarios modeled. This is mostly the result of the assumed single service life extension for existing nuclear units and the limited growth in nuclear capacity under the assumptions used.

77. In this section, penetration refers to the annual percentage of energy sourced from wind power plants. The prescribed wind penetration levels associated with the *Study Scenario* of 10% by 2020, 20% by 2030, and 35% by 2050 for the continental United States reflect the annual electricity generated by wind power plants divided by annual end-use electricity demand. When regional wind penetration levels are displayed in this section, the denominator is instead represented by the total annual electricity generated in that region.

The modeled scenarios are developed using the ReEDS long-term nationwide capacity expansion model described in Section 3.1.1, which is designed to consider the major grid integration issues surrounding future electricity infrastructure development. The present analysis is not intended to be a full integration study that relies on hourly or sub-hourly modeling; instead, it provides a high-level and semi-quantitative assessment of the grid integration challenges at high wind penetration. The scenario analysis complements and is supported by the conclusions found in integration studies, including those that evaluate 30–50% wind and solar penetration levels [2, 63, 64, 65, 66, and others]. Further work could provide additional high-resolution insights specific to the transmission and integration impacts of the *Study Scenario.*

Notwithstanding the limitations of the *Wind Vision* analysis discussed here, the ReEDS scenarios provide a general assessment of the impacts of greater wind deployment, including issues around system operations and transmission expansion. In addition, while the analysis focuses on wind integration, many of the practices and technologies described to support greater wind deployment can have system-wide benefits even without wind.

3.6.1 Integrating Variable and Uncertain Wind Energy

The *Study Scenario* includes wind penetration levels that are significantly higher than the 4.5% penetration level experienced in 2013 [4] . In this section, the impacts of this increased wind penetration level to system operations are considered in terms of wind capacity value or contributions to system planning reserves, impacts to operating reserves, and wind curtailments. Regional implications are also explored.

At the planning timescale, ReEDS estimates that the capacity value[78] of wind (i.e., the contribution of wind in providing firm capacity planning reserves to meet peak or net peak[79] demand hours) declines with increasing wind penetration. For example, for the *Study Scenario*, ReEDS estimates the *average* capacity value of the entire wind fleet providing 35% of 2050 demand to be about 10–15%, and the *marginal* capacity value to be near zero in most regions.[80] Accordingly, wind's aggregate contribution to planning reserves is relatively modest compared to its nameplate capacity, and new plants installed late in the period of analysis have zero contribution to planning reserves. This result does not imply that new wind deployment causes a need for more capacity, nor does it create new peak planning reserve *requirements*. It does, however, reflect that wind may not reduce the need for new capacity as much as alternative resources with higher capacity value. In other words, a consequence of low marginal wind capacity value is that non-wind options, including new thermal generation, demand-side resources, or other options may be needed to ensure sufficient planning reserves due to peak electricity demand growth.

At operational timescales, ReEDS ensures that capacity reserves are held to adequately meet operating requirements, including contingency, regulation, and forecast error reserve requirements.[81] Changes in the requisite operating reserve capacity resulting from increased wind deployment are modeled in ReEDS through increased forecast error reserve requirements. For example, wind forecast error reserves of approximately 10–15% of wind capacity are estimated for the *Study Scenario*. As a result, the *Study Scenario* requires that a greater amount of capacity is available to providing operating reserves compared to the *Baseline Scenario*. This result does not necessarily

78. Capacity value is a statistical metric used to identify the amount of a power plant's (or technology group's) total nameplate capacity that can be reliably used during peak hours [68, 69]. Effective load-carrying capacity calculations are widely accepted reliability-based methods used to estimate wind capacity value. ReEDS uses simplified effective load carrying capacity calculations to estimate wind and solar capacity value dynamically for all regions, penetration levels, and system configurations [70].

79. Net peak hours occur when electricity demand minus variable generation is highest.

80. Marginal values reflect the capacity value for the next increment of wind capacity, while average values reflect the capacity value for the entire amount of wind capacity in a region in existence as of that year.

81 Contingency reserves are used to address unexpected generator or transmission outages. The amount of contingency requirement is typically assessed based on the largest generating unit or transmission line in a region. Regulation refers to the very short (less than 5-minute) timescale deviations between generation and load. ReEDS allows regions to trade reserve capacity (operating and planning) between model regions, but constrains the amount of trading by the available transmission capacity. ReEDS assumes contingency and regulation reserves to be 6% and 1.5% of demand, respectively, in every model balancing area. ReEDS treatment of operating reserves is described in Short et al. 2011 [3] and Mai et al. 2014 [10].

imply that new capacity is needed to provide these reserves, but that greater existing (or new) capacity is online or can be made readily available at the operating timescale (hourly or shorter). Increased wind penetration could free up other generators to provide operating reserves instead of energy [63, 67]. Increased operating reserve requirements could impose higher costs or prices for ancillary services [67]. Such potential cost increases may be offset by lower wholesale energy prices that result from increased wind penetration at least in the short run (see Text Box 3-6). The net cost implications of increased operating reserves and other grid integration issues are included in the ReEDS scenario cost estimates described in Section 3.4.

The ReEDS analysis does not consider a number of other short timescale grid services needed to ensure system reliability, including voltage stability, inertia, and frequency response. Other studies (e.g., [71]) have evaluated the effects of wind penetration on these services, and further research is needed to examine them for the *Study Scenario*. Wind power plants with active power control can provide a range of ancillary services, including synthetic inertia, regulation, reactive power, voltage support, and contingency reserves.[82]

Increased wind penetration also creates the potential for greater wind curtailment. ReEDS estimates the amount of wind curtailment (the amount of wind energy available but not used due to transmission constraints and/or system inflexibility) across all scenarios. Wind curtailment amounts of approximately 20 TWh (2% of annual wind generation) in 2030 and 50 TWh (3%) in 2050 are estimated for the *Central Study Scenario*.[83] On a percentage basis, these curtailment values are similar to wind curtailments experienced leading up to 2013 across many regions of the United States [72]; however, the *Study Scenario* includes much higher levels of wind deployment than existed in 2013. Many factors affect curtailment, including the efficiency of resource sharing across balancing areas, which is assumed to be highly efficient within the system-wide optimization construct in ReEDS. Generator flexibility, including the ability to operate at a low generation point, ramp rapidly, and start/stop, can also have substantial effects on curtailment. While the curtailment values for the *Study Scenario* are low, marginal curtailment values can be higher and potentially impose challenges to investment decisions for new wind capacity.[84]

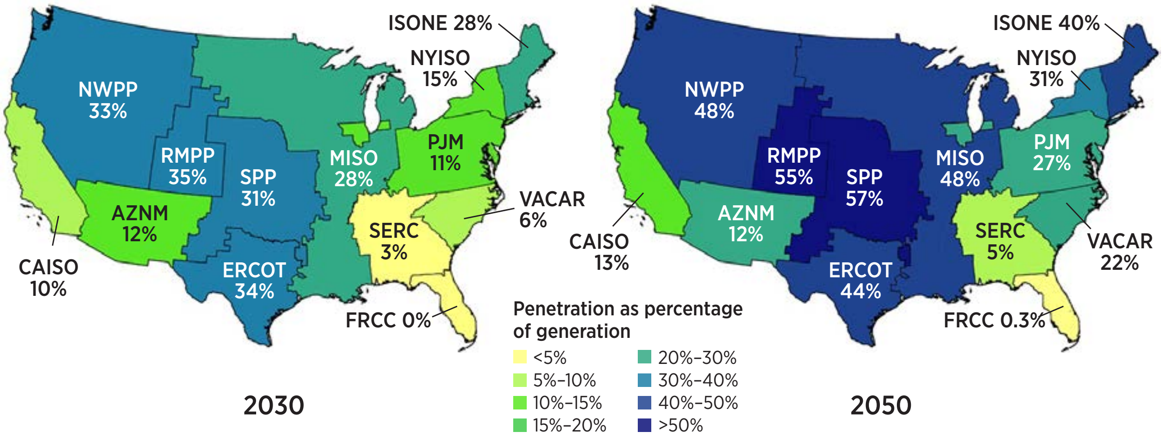
The ReEDS analysis finds that wind curtailment occurs most prominently during times of low demand and high wind generation, which coincide with spring nights for many regions in the United States. Under high wind penetration regimes, grid integration challenges are found to be generally most acute during these same time periods. This includes increased ramping and cycling of thermal power plants in addition to curtailments [2, 65]. More detailed hourly or sub-hourly modeling would be needed to better estimate and understand wind curtailment and operational changes under the *Wind Vision Study Scenario*.

While the prescribed wind penetration levels apply to the continental United States as a whole, the variations in wind quality and relative distances to load centers and the existing infrastructure drive regional differences in wind penetration levels. Figure 3-26 shows these differences for 2030 and 2050 in the *Central Study Scenario*. In 2030, many regions in the western, central, and northeastern parts of the United States have penetration levels that exceed the 20% nationwide level, with some regions exceeding 30% penetration. Resource limitations for land-based wind diminish wind growth in some regions (e.g., California and the southeastern United States). Under the *Central Study Scenario*, however, wind capacity is found across nearly all states by 2030. By 2050, regional wind penetration levels exceed the 35% nationwide *Study Scenario* level in many regions, especially in the western and central parts of the United States. Only two regions in the Southeast have wind penetration levels below 20% by 2050 and, in fact, are well below 10%. Figure 3-26 demonstrates that grid integration challenges will vary in magnitude and timing between regions.

82. Wind's low energy cost typically makes wind a higher-cost option for ancillary service supply than thermal generation, due to the higher opportunity cost incurred when wind curtails energy production in order to make capacity available for reserves. If wind is curtailed for other reasons (minimum load limits on thermal generation, for example), it can be a cost-effective ancillary service provider.

83. Curtailment values can vary significantly between regions.

84. The LCOE of wind is inversely proportional to the amount of energy wind provides; therefore, increased curtailment would increase this cost.



Note: The percentages shown reflect the percentage of in-region wind generation to in-region total generation. They do not take into account imports or exports of electricity, including any imports from Canada. The regions depicted represent approximate boundaries of existing regional transmission organizations/independent system operators (RTOs/ISOs) and other reliability areas to illustrate regional wind penetration distributions only. They do not reflect future expected market, energy balancing or reserve sharing boundaries. Acronyms used in this map: Northwest Power Pool (NWPP); California ISO (CAISO); Western Electricity Coordinating Council /Southwest (AZNM); Rocky Mountain Power Pool (RMPP); Electric Reliability Council of Texas (ERCOT); Southwest Power Pool (SPP); Midcontinent ISO (MISO); SERC Reliability Corporation (SERC); Virginia-Carolinas Region (VACAR); PJM Interconnection (PJM); New York ISO (NYISO); ISO New England (ISONE); Florida Reliability Coordinating Council (FRCC).

Figure 3-26. Regional annual wind penetration for 2030 and 2050 under the *Central Study Scenario*

These findings demonstrate some of the grid integration challenges associated with greater wind deployment. In combination with a large body of renewable grid integration studies (e.g., [2, 63, 64, 65, 73]), they also indicate that these challenges can be mitigated through a portfolio of supply-side, demand-side, and market solutions to increase system flexibility. This includes coordination over wider areas, increased transmission, improved wind forecasting, faster dispatch and commitment schedules, demand response, electric vehicles, wind curtailment, and storage.[85] Similar to the regional variations of the grid integration challenges posed in the *Study Scenario*, as indicated by Figure 3-26, the deployment of mitigation options will also vary by region. The cost impacts presented in Section 3.4 include the costs to deploy the mitigation options as assumed in ReEDS. ReEDS does not represent all flexibility options, nor does it comprehensively assess their costs and value. It does, however, give an indication of the potential deployment of a subset of options. For example, the *Central Study Scenario* results in about 28 GW of total installed storage capacity by 2030 and 54 GW by 2050. In contrast, there are approximately 22 GW of operating storage capacity in the U.S. electric system, and 24 GW installed by 2050 in the *Baseline Scenario*. These results are reflective of the assumptions used for storage and other flexibility options and the associated representation in ReEDS. Greater understanding of the costs and benefits of storage and other mitigation options to support higher wind penetrations would be needed to more accurately estimate future adoption of flexibility technologies and practices.

Text Box 3-4 summarizes the grid integration challenges associated with the *Study Scenario* (across sensitivities). It also summarizes the estimated transmission needs of the *Central Study Scenario* as discussed in greater detail in the following section.

85. Synergies between nightly electric vehicle charging and excess wind energy exist [74, 75, 76], as advanced controls on vehicle charging can enable demand response to provide additional reserves required to accommodate wind integration.

Text Box 3-4.

Transmission and Grid Integration Challenges of the *Wind Vision*

The variable, uncertain, and location-dependent nature of wind energy introduces grid integration challenges associated with the *Wind Vision.*

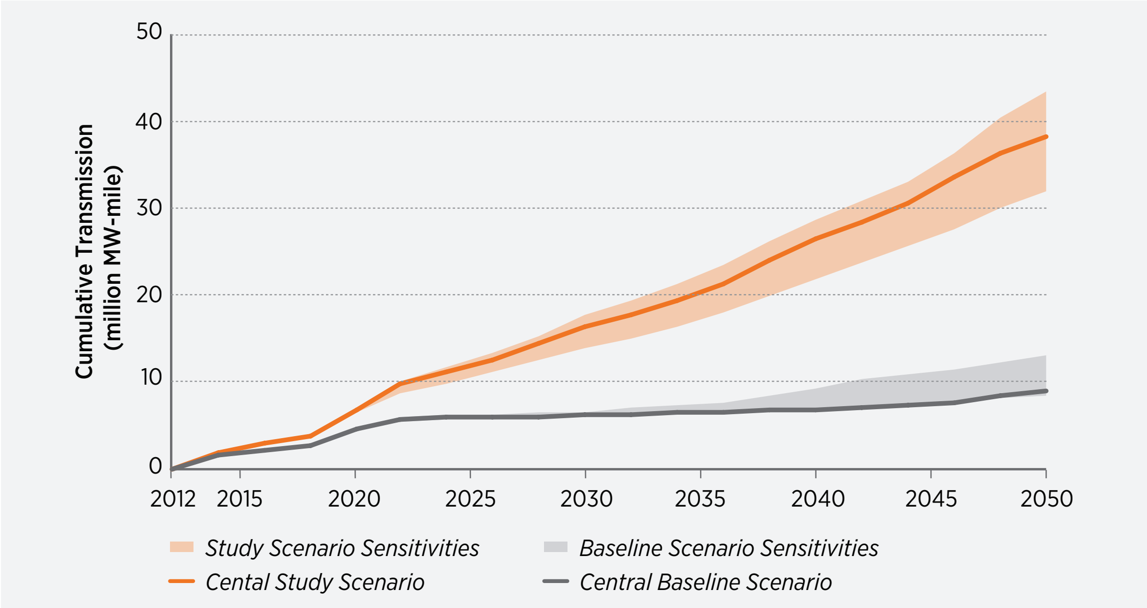
Planning Reserves: The contribution of wind as a firm capacity resource to meet long-term planning reserves typically declines with increasing wind penetration [68, 69]. ReEDS estimates that the aggregate capacity value of the wind fleet is about 10–15% in 2050, when wind penetration reaches 35%. Marginal capacity value can be even lower, and near zero for many regions. While adding wind does not increase planning reserve requirements, wind's low capacity value implies that other sources may be needed to meet any potentially growing peak system adequacy requirements.

Operating Reserves: Wind energy cannot be perfectly predicted and can introduce increased ramping needs. The typical means of managing these needs is to increase operating reserve requirements and hold greater amounts of reserve capacity online. ReEDS estimates increased operating reserve requirements of 10–15% of wind capacity in 2050. Increased reserves can incur greater costs and prices for ancillary services [67]. These costs are captured in the cost results presented in Section 3.6, with much of the need being serviced by existing generators.

Wind Curtailments: The inherent variability of wind energy, in combination with system inflexibility such as transmission constraints and physical generator limits, can lead to wind curtailment [72]. ReEDS estimates that 2–3% of potential wind energy is curtailed in 2050. Curtailment influences the economic position of wind, but can be a source of valuable system flexibility that can reduce the cost of managing the electric system's supply and demand balance [71].

Mitigation Options: Diverse options are available to help manage the variability and uncertainty of wind. These include market and institutional solutions (e.g., wider area coordination, faster commitment and dispatch schedules), operational practices (e.g., improved forecasting, increased dispatch flexibility, curtailments), technology solutions (e.g., storage, demand-side options), and transmission expansion. ReEDS estimates an incremental 29 GW of storage capacity in the *Central Study Scenario* by 2050, relative to the *Baseline Scenario.* The costs to deploy storage are captured in the cost results presented in Section 3.6 but further work is needed to understand the cost and benefits of different mitigation solutions. These solutions increase overall flexibility and could garner benefits to the system even absent wind.

Transmission Expansion: Transmission infrastructure expansion is needed to access and deliver remote wind resources to load centers. It also helps facilitate resource sharing between regions. ReEDS estimates a cumulative incremental transmission need of 29 million MW-miles (or 32,000 circuit-miles, assuming 900-MW single-circuit 345-kV lines are used to meet this increment) by 2050 for the *Study Scenario,* relative to the *Baseline Scenario.* Challenges with transmission expansion include siting and cost allocation, but advanced transmission options such as high-voltage direct-current and transmission switching [77] can further support system flexibility.



Note: Figure depicts cumulative transmission measured from 2013 up to the x-axis year.

Figure 3-27. Cumulative transmission expansion under the *Baseline Scenario* and *Study Scenario*

3.6.2 Transmission Expansion Needed to Support the *Wind Vision*

The ReEDS analysis estimates increased transmission expansion in the *Study Scenario* compared with the *Baseline Scenario*. Figure 3-27 shows the cumulative transmission expansion needs estimated for the *Central Study Scenario* and *Baseline Scenario* as well as the range of results across the sensitivity scenarios. Between 2013 and 2020, as shown by the differences in transmission expansion between the two *Central* scenarios in Figure 3-27, estimated incremental transmission needs to support the *Central Study Scenario* total 2.3 million MW-miles.[86] By 2030 and 2050, these *incremental* transmission demands increase to 10 and 29 million MW-miles, respectively.[87] For comparison, the existing transmission system in the United States totals approximately 200 million MW-miles [78].[88] In other words, while the new transmission requirement in the *Central Study Scenario* is 2.7 times greater than in the *Baseline Scenario* by 2030 and 4.2 times greater by 2050, the total transmission needs of the *Central Study Scenario* would expand the *existing* transmission network by less than 10% by 2030 and by less than 20% by 2050.

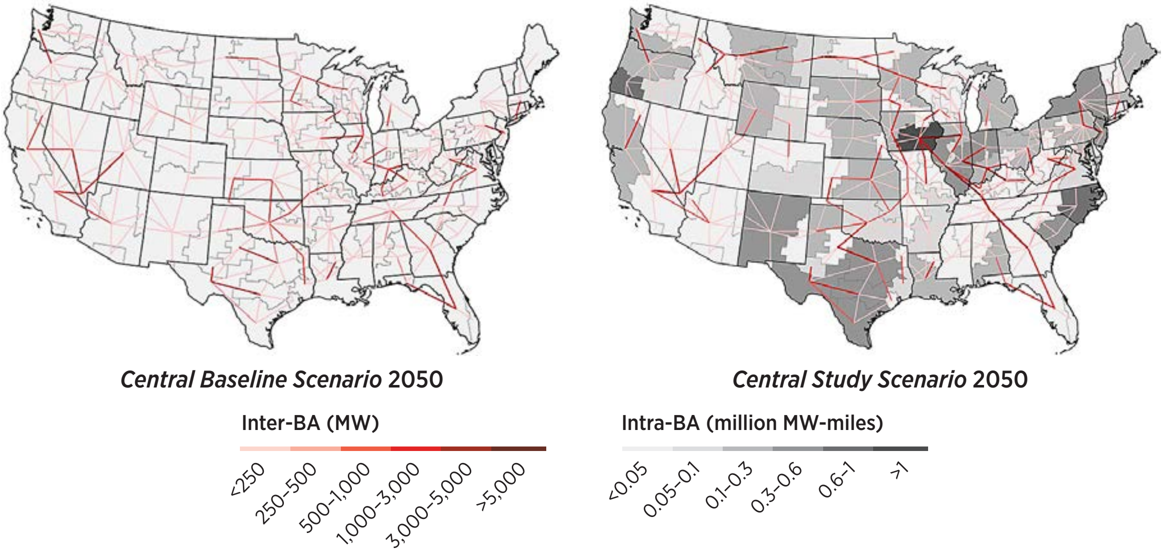
The incremental transmission needs of the *Central Study Scenario* relative to the *Baseline Scenario* can be expressed in units of circuit miles by assuming that the representative transmission line used has a carrying capacity of 900 MW, which is typical for single-circuit 345-kV lines.[89] Under this assumption, cumulative

86. Modeled transmission infrastructure is presented using the unit MW-mile, which represents a transmission line rated with a carrying capacity of 1 MW of power and a 1-mile extent. The amount of new transmission includes long-distance interregional transmission lines as well as spur lines used for grid interconnection of new wind capacity. Planned and under-construction transmission projects are included in ReEDS and reported in Appendix G.

87. The range of incremental cumulative (from 2013) transmission expansion estimated across all *Study Scenario* sensitivities is 7–12 million MW-miles by 2030 and 18–34 million MW-miles by 2050.

88. For another comparison, all interregional lines in the existing transmission network are represented in ReEDS as 88 million MW-miles; however, this metric excludes all lines that do not cross model region boundaries. The scenario-specific transmission expansion results include both inter-regional and intra-regional lines. For the *Study Scenario* sensitivities, estimates are that approximately one-third of the total transmission needs are for intra-regional lines.

89. The selection of single-circuit 345 kV as the representative transmission line is only used to provide a simple estimate of circuit miles. Future transmission expansion will rely on different voltages and technologies, and will result in different distance estimates for the incremental transmission needs of the *Study Scenario*.



Note: Red lines represent long-distance interregional transmission, and gray shades represent intraregional lines, primarily to interconnect new wind capacity. Transmission model regions in ReEDS are referred to as balancing areas (BAs) in the figure. While boundaries of real balancing authority areas help inform the design of the model BAs, the ReEDS BAs do not necessarily correspond with real balancing authority areas. Real balancing authority areas boundaries have evolved and are constantly evolving. Thus, model alignment under this dynamic condition has not been attempted.

Figure 3-28. New (2013–2050) transmission expansion under the *Central Baseline Scenario* and *Study Scenario*

incremental transmission needs of the *Central Study Scenario* total about 11,000 and 33,000 circuit miles of new transmission by 2030 and 2050, respectively. These values correspond to an average of 350 circuit miles/year between 2014 and 2020, 890 miles/year between 2013 and 2030, and 1,050 miles/year between 2031 and 2050. For comparison, North American Electric Reliability Corporation (NERC) [79] reports that, since 1991, an average of 870 miles/year of new transmission have been added and 21,800 circuit miles are planned with in-service dates before 2023.[90]

On a present value basis, total transmission-related expenditures comprise less than 2% of total system costs[91] for the *Study Scenario* sensitivities (see Section 3.4.2). Such costs include all fuel, O&M, and capital expenditures. The present value of incremental transmission-related expenditures of the *Central Study Scenario* compared to the *Baseline Scenario* totals $60 billion. As a linear optimization model, however, ReEDS likely underestimates the amount of transmission needed due to the lumpy nature of transmission investments, non-direct paths in real transmission lines compared to the point-to-point model paths, and siting and permitting challenges for these infrastructure investments. ReEDS also does not estimate the cost to maintain the existing transmission grid, which would have a similar effect to the *Baseline Scenario* and *Study Scenario*. In addition, construction of new transmission lines can serve reliability and other purposes that are beyond the scope of the ReEDS model. For this reason, the total amount of transmission expansion and associated costs estimated for both the *Baseline* and *Study Scenarios* are likely understated. Including transmission maintenance costs or other modifications to the economic representation of transmission deployment in ReEDS would likely only have minor effects on the amount of total system cost for transmission-related expenditures.

Figure 3-28 shows the location of new transmission paths estimated by ReEDS for the *Central Baseline Scenario* (left) and *Central Study Scenario* (right).

90. The regions assessed by NERC also include Canadian provinces and a portion of northern Baja Mexico.

91. The present value (2013-2050, 3% discount rate) of transmission-related costs are estimated to be about $70 billion for the *Central Study Scenario* and range from $62 billion to $79 billion across all *Study Scenario* sensitivities. On an undiscounted basis, average annual transmission expenditures totals about $4 billion per year for the *Central Study Scenario* between 2013 and 2050.

In addition to the increased magnitude of new transmission infrastructure estimated for the *Study Scenario* relative to the *Baseline Scenario*, the geographic distribution also differs between these two scenarios. In particular, though new transmission is generally uniformly distributed across the continental United States under the *Baseline Scenario*, somewhat higher concentrations of transmission projects are found in certain regions including the Midwest, the south central states, the West, and the northern Atlantic region under the *Study Scenario*. These new transmission locations reflect the geographic location of high quality land-based wind regions relative to the load centers.

The ReEDS model co-optimizes transmission and generation expansion, but it is not designed to formulate a coordinated transmission plan. Others have explored transmission network options to help support expansion of wind and other renewable technologies and to support improved reliability (e.g., [80]). In particular, numerous high-voltage direct-current (HVDC) projects are in various development stages. These projects can enhance coordination over long distances and help system operators and regional reliability organizations manage increased variability due to higher wind deployment. Further research would be needed to evaluate transmission plans and technologies to enable cost-effective access of high-quality wind. Further research would also be needed on the additional benefits that advanced technologies like HVDC can provide in terms of stability, contingency reserves, and greater operating flexibility, with or without additional wind.

3.7 Greenhouse Gas Emissions Reductions

The majority of scientists agree that significant changes will occur to the Earth's climate on both a multi-decadal and multi-century scale as a result of past and future GHG emissions. These changes may include rising average temperatures, increased frequency and intensity of some types of extreme weather, rising sea levels due to both thermal expansion and ice melt, and ocean acidification [81, 82, 83, 84, 85, 86]. In part as a result, there is growing agreement among scientists and economists on the desirability of near-term rather than delayed actions to reduce GHGs [87, 85, 88, 89].

Wind power is one of a family of clean energy technologies[92] that could be deployed to reduce GHG emissions, in turn decreasing the likelihood and severity of future climate-related damages [84, 85]. Additionally, near-term action to limit GHGs may lessen the longer-term cost to society of meeting future policies intended to reduce GHGs [90]. Some states (e.g., California) and regions (e.g., a number of northeastern states) have already enacted carbon policies [90], and the U.S. Congress has also considered such policies [90]. The U.S. EPA has implemented GHG reduction programs for the transport sector [91] and has proposed carbon dioxide emission limits for new and existing power plants [92]. In part as a result, utilities regularly consider GHG regulatory risk in resource planning [93, 94].

This section first estimates the potential GHG reductions associated with the *Study Scenario* compared to the *Baseline Scenario*, on both a direct-combustion and life-cycle basis.[93] It then quantifies the economic benefits of these GHG reductions based on the range of social cost of carbon estimates developed by the U.S. IWG and used by the U.S. government [95, 96]. The methods applied here are consistent not only with those used by U.S. regulatory agencies [97], but also with those used in the academic literature [98, 99, 100, 101, 102]. Text Box 3-5 also briefly summarizes the literature on the net energy requirements of different electricity generation technologies. Net energy is another metric often used to compare energy technologies on a life-cycle basis, and one in which wind energy performs relatively well in comparison to other electricity generation sources.

92. Including other forms of renewable energy, nuclear, fossil-based carbon capture and sequestration, and energy efficiency.

93. This section evaluates the impacts of the *Study* and *Baseline Scenarios,* under *Central* assumptions only. The ranges presented in this section are driven by the range of parameters evaluated and not by the range of scenario results.

3.7.1 Wind Energy Reduces GHG Emissions

Achieving the wind deployment levels of the *Study Scenario* will reduce fossil energy use (see Section 3.5), leading to reduced fossil fuel-based carbon emissions in the electric sector. Figure 3-29 shows the decline in annual combustion-related carbon emissions (left panel) and annual life-cycle emissions (right panel) for the *Study Scenario* relative to the *Baseline Scenario*.

Based on output from ReEDS, the left panel of the figure shows that, by 2050, direct combustion CO_2 emissions are estimated to decline by 23% in the *Study Scenario* relative to the *Baseline Scenario*.[94] Cumulative emissions from 2013-2050 are 13% lower in the *Study Scenario* than in the *Baseline Scenario*.

The estimates of combustion-related emissions in the left panel of Figure 3-29, however, do not consider several potentially important effects. First, only CO_2 emissions are considered while other potent GHGs are ignored, an omission that may be particularly important for methane released in coal mining, oil production, and natural gas production and transport. Second, and related, only emissions from the combustion of fossil energy are counted, while emissions from upstream fuel extraction and processing are disregarded. Finally, a focus on combustion-only emissions means that the GHG emissions from equipment manufacturing and construction, O&M activities, and plant decommissioning are not considered for wind or any other electric power plants.

A more comprehensive evaluation requires that GHG emissions across the full life cycle of each technology be evaluated with life-cycle assessment (LCA) procedures, and the results of this assessment are presented in right panel of Figure 3-29.[95] In particular, an extensive review and analysis of previously published LCAs on electricity generation technologies was

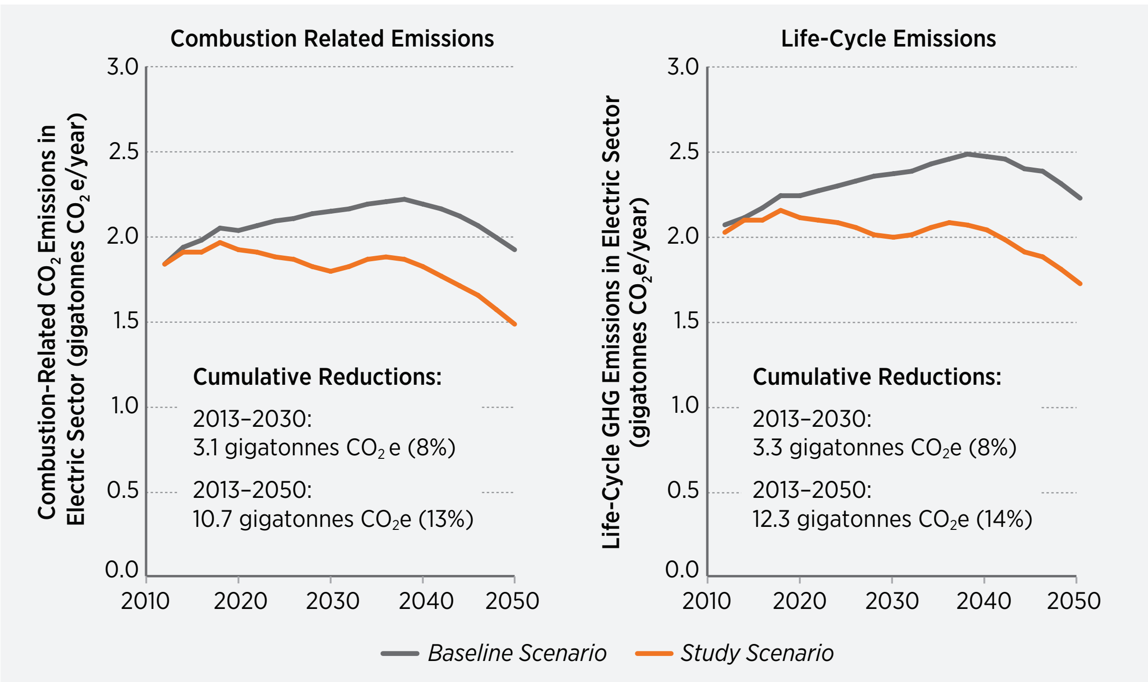
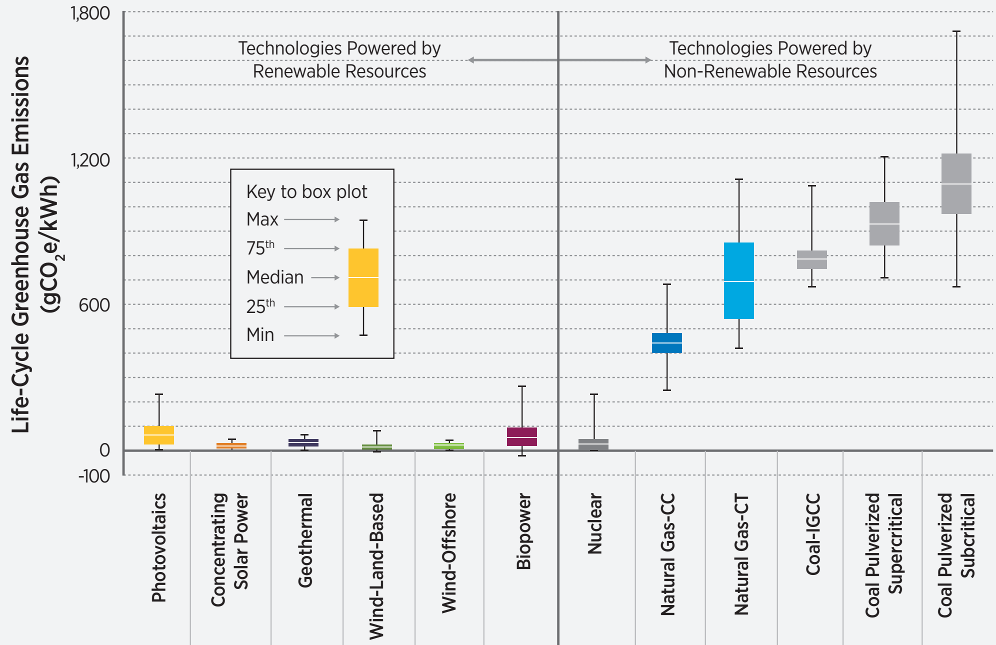


Figure 3-29. Greenhouse gas emissions in the *Central Study Scenario* and *Baseline Scenario*

94. Unless otherwise noted, all reported values related to carbon dioxide or GHG emissions are in units of metric ton (i.e., tonne) of CO_2 or CO_2 equivalent (CO_2eq).

95. A full LCA considers upstream emissions, ongoing combustion and non-combustion emissions, and downstream emissions. Upstream and downstream emissions include emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, on-site construction, project decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the equipment and other site material.



	Photovoltaics	Concentrating Solar Power	Geothermal	Wind-Land-Based	Wind-Offshore	Biopower	Nuclear	Natural Gas-CC	Natural Gas-CT	Coal-IGCC	Coal Pulverized Supercritical	Coal Pulverized Subcritical
Estimates (count)	124	20	8	154	32	102	99	55	22	21	17	120
References (count)	26	7	6	62	18	26	27	34	11	16	7	41

Note: Acronyms used in this figure: Natural Gas-CC = Natural gas combined cycle; Natural Gas-CT = Natural gas combustion turbine; Coal - IGCC = Coal integrated gasification combined cycle

Source: Mai et al. [2]

Figure 3-30. Summary of systematic review of estimates of life-cycle GHG emissions from electricity generation technologies

conducted through the LCA Harmonization project.[96] For the *Wind Vision* analysis, this foundation was augmented by the assessment of additional LCA literature for wind technologies, published through August 2013. Figure 3-30 summarizes the results of this extensive literature review for a wide range of renewable and non-renewable electricity generation technologies, including the full range of estimates of life-cycle emissions factors for each technology. (See Appendix J for further details for wind, including a listing of the large number of publications reviewed. For all other technologies, see Appendix C, Volume 1 of *Renewable Electricity Futures* [2]).[97] Based on this comprehensive literature assessment, the median life-cycle, non-combustion GHG emission values for each generation technology were used to estimate GHG emissions that are in addition to the ReEDS-calculated combustion-only CO_2 emissions shown in the left panel of Figure 3-29.

96. *http://www.nrel.gov/harmonization*

97. The life-cycle GHG emissions for natural gas-fired combustion technologies has recently become a topic of intense interest and debate. Two meta-analyses of available LCAs were published in 2014: O'Donoughue et al. [103] harmonized estimates for electricity generated using conventionally produced natural gas; Heath et al. [104] harmonized evidence for unconventional natural gas. Both support the prevailing view that, on average, life-cycle GHG emissions from natural gas-fired generators are half that of coal, though there could be cases with emissions much higher. Measurements in some natural gas production basins, e.g., [105, 106] suggest higher methane leakage rates than have typically been included in the harmonized LCAs. These have, however, only measured a few, small basins, and not enough evidence is available to develop a national average based on measurements. A 2014 synthesis of measurement evidence of methane leakage from natural gas systems [107] concludes that natural gas retains climate benefits over coal, even considering the available evidence from measurements. The *Wind Vision* report uses the available LCA literature to assign GHG emission estimates to each life-cycle stage. These assignments could be updated as new evidence becomes available.

The extensive literature demonstrates that, on a life-cycle basis, wind has among the lowest levels of GHG emissions of different energy technologies (Figure 3-30). As a result, when considering the full life-cycle, Figure 3-30 (right panel) shows that the *Study Scenario* is estimated to significantly reduce GHG emissions in the electric sector relative to the *Baseline Scenario*: 6% in 2020 (0.13 gigatonnes CO_2e), 16% in 2030 (0.38 gigatonnes CO_2e), and 23% in 2050 (0.51 gigatonnes CO_2e). Cumulative life-cycle GHG emissions are reduced by 12.3 gigatonnes CO_2e from 2013 to 2050 (14%). Life-cycle GHG reductions are larger in absolute terms than combustion-only CO_2 reductions.

These estimates suggest significant potential for wind energy in reducing GHG emissions, consistent with previous literature [1, 28].The foregoing analysis, however, does not consider two factors that may degrade to a degree the actual emissions savings from increased wind deployment. First, the GHG benefits of variable renewable generation may be eroded to a degree by the increased cycling, ramping, and partial loading required of conventional generators. Partial loading of fossil generators, for example, means operating those plants at less-efficient output levels. This creates a penalty for fuel efficiency and GHG emissions relative to optimally loaded plants. Though the analysis discussed here does not capture these effects, the difference implied by this omission is, in this case, expected to be modest. The reduction in GHG benefits can be significant when considering small, isolated systems with little geographic diversity of wind and few plants to offer balancing services, but the effects are much smaller in large systems—such as those analyzed here—with many conventional generators and considerable smoothing from geographic diversity [108, 109]. Recent studies have found that the GHG emissions benefits of wind energy are diminished by, at most, less than 10% [110, 111, 112,113]. In the largest and most sophisticated of these studies, Lew et al. [65] find that the emissions impact is negligible (less than 1%).

Second, economy-wide rebound and spillover effects can impact emissions reductions, especially when those rebound and spillover effects are affected by policy mechanisms.[98] The model used for the *Wind Vision* analysis focuses on the electric sector, and the analysis is intentionally policy-agnostic. This voids the opportunity for an assessment of economy-wide spillover or rebound effects. Other literature, however, has shown that spillover and rebound effects can impact GHG savings, as can the specific policy mechanisms used to support renewable energy deployment. In particular, there is general agreement that GHG savings will be greater and/or achieved at lower cost when met, at least in part, through economy-wide carbon pricing, and lower when met solely through sector-specific financial incentives for low-carbon technologies [48, 49, 50, 85, 114, 115, 116, 117, 118, 119]. Depending on the policies employed and related rebound and spillover effects, the GHG reductions estimated here may therefore over- or under-state actual emissions reductions associated with the wind deployment levels envisioned in the *Study Scenario*.

3.7.2 Economic Benefits of Wind Energy in Limiting Climate Change Damages

The economic benefits of wind energy due to limiting damages from climate change can be estimated through the use of a metric known as the social cost of carbon, or SCC. The SCC reflects, among other things, monetary damages resulting from the future impacts of climate change on agricultural productivity, human health, property damages, and ecosystem services [95, 96].The methodology for estimating the benefits from reduced GHG emissions involves multiplying the emissions reduction (on a life-cycle, CO_2eq basis) in the *Study Scenario* (relative to *Baseline Scenario*) in any given year by the SCC for that year, and then discounting those yearly benefits to the present.[99]

Estimating the magnitude and timing of climate change impacts, damages, and associated costs is challenging, especially given the many uncertainties involved [81, 84, 85, 86, 95, 96, 120, 121]. Models of climate response to GHG emissions and damage functions associated with that response are imperfect. Even when looking to events over the several decades leading up to 2013, such as the upward trend in damage costs associated with extreme environmental events [122], caution is necessary to separate causation from correlation [123]. In addition, because the majority of effects will be felt many decades and even centuries

98. As one example, if policies used to support wind development tend to decrease retail electricity prices, then customer incentives for energy efficiency will be muted, potentially reducing GHG savings. The opposite would be anticipated if retail electricity prices increase.

99. The discount rate varies for any individual calculation to be consistent with that assumed in the SCC estimate.

in the future, the choice of discount rate becomes a key concern when estimating the present value of future damages. This can, in turn, greatly influence the relative benefits and timing of alternative strategies to reduce carbon emissions [124, 125].

In part as a result, a number of widely ranging estimates of the SCC are available [85, 120, 126]. Key uncertainties about the SCC result from: (1) difficulties in estimating future damages associated with different climate-related causes, as well as uncertainties about the likelihood, timing, and potential impact of (nonlinear) tipping points; (2) the high sensitivity of the SCC to assumptions about growth in world population, gross domestic product, and CO_2 emissions; and (3) large differences in the present value of estimated damages depending upon choice of discount rate [120, 127, 128].

Though these uncertainties have led some to suggest possible improvements to SCC estimates [125, 129, 130, 131] or even to question the use of these estimates [128], U.S. government regulatory bodies now regularly use SCC estimates when formulating policy [97, 130]. Under Executive Order 12866,[100] U.S. agencies are required, to the extent permitted by law, to assess costs and benefits—even though these are considered difficult to quantify—during regulatory proceedings. To that effect, in 2010, the U.S. IWG on the SCC[101] used three integrated assessment models to estimate the SCC under four scenarios [95]. The IWG SCC reflects *global* damages from GHGs, and IWG recommends use of global damages. That approach is followed in the *Wind Vision*, recognizing that lower values are obtained if only damages within the United States are considered.[102] In 2013, IWG updated its estimates based on improvements in the integrated assessment models, which lead to an increase in SCC values [96]. IWG SCC estimates have been widely used in regulatory impact analyses in the United States, including in numerous proposed or final rules from the EPA, DOE, and others [97].

To reflect the inherent uncertainties, the IWG [96] has published four SCC trajectories (see Figure 3-31 for these four trajectories from 2010 to 2050). Three of the four trajectories are based on the expected value of the SCC (estimated by averaging the results of the three IWG models), assuming discount rates of 2.5%, 3%, and 5%.[103] A fourth trajectory represents a 95th percentile of the SCC estimates across all three models at the central 3% social discount rate. This 95th percentile case is intended to reflect a much less likely outcome, but one with a much higher than expected impact, e.g., due to more extreme temperature changes.[104]

Using the four IWG SCC estimates, Figure 3-32 shows the present value of the estimated global benefits of life-cycle GHG reductions from 2013 to 2050 from the *Study Scenario* (compared to the *Baseline Scenario*, and assuming no rebound or spillover effects). For the IWG central value case, discounted present-value benefits are estimated to be $400 billion. Across the three expected-value cases, benefits range from $85 billion (for the 5% discount rate case) to $640 billion (for the 2.5% discount rate case). The fourth case that accounts for the small possibility of more extreme effects results in a benefit estimate of $1,230 billion.[105,106]

100. *http://www.archives.gov/federal-register/executive-orders/pdf/12866.pdf*

101. U.S. agencies actively involved in the process included the EPA and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury. The process was convened by the Council of Economic Advisors and the Office of Management and Budget, with active participation from the Council of Environmental Quality, National Economic Council, Office of Energy and Climate Change, and Office of Science and Technology Policy.

102. The IWG notes that a range of values from 7–23% should be used to adjust the global SCC to calculate domestic effects, but also cautions that these values are approximate, provisional, and highly speculative [95].

103. The use of this range of discount rates reflects uncertainty among experts about the appropriate social discount rate [95, 129].

104. Each of the integrated assessment models estimates the SCC in any given year by modelling the impact of CO_2 emissions in that year on climate damages over a multi-century horizon (discounted back to that year). The SCC increases over time because, as IWG explains, "future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climate change" [96].

105. As suggested by the IWG, domestic benefits might be 7–23% of these global estimates [95].

106. Annual benefits reflecting the discounted future benefits of yearly avoided emissions are as follows: (1) low: $1.8 billion (2020), $7.0 billion (2030), $15.5 billion (2050); (2) central: $6.3 billion (2020), $22.8 billion (2030), $42.3 billion (2050); (3) high: $9.4 billion (2020), $32.9 billion (2030), $57.8 billion (2050); (4) higher-than-expected: $18.9 billion (2020), $69.7 billion (2030), $131.0 billion (2050) [2013$].

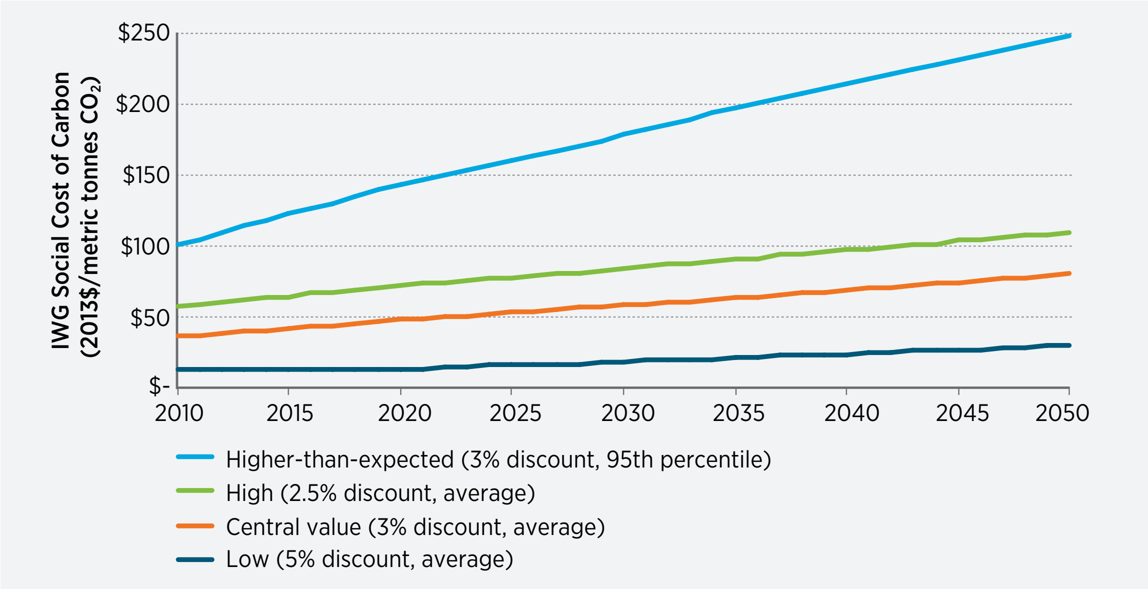


Figure 3-31. IWG social cost of carbon estimates

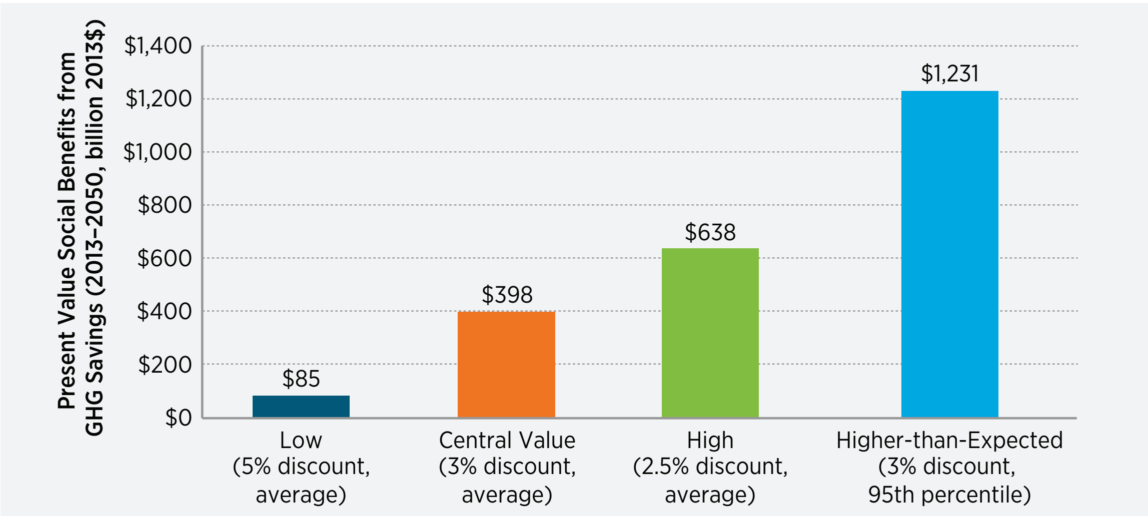


Figure 3-32. Estimated benefits of the *Study Scenario* due to avoided climate change damages

To put these figures in another context, the central value estimate represents a levelized global benefit of wind energy of 3.2¢/kWh of wind. Across the remaining three scenarios, the estimated GHG savings benefit ranges from 0.7¢/kWh of wind (low) to 5.2¢/kWh of wind (high) to 10¢/kWh of wind (higher than expected).[107]

107. These **levelized** impacts are calculated by dividing the discounted benefits by the discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario.* When instead presented on a **discounted,** average basis (dividing discounted benefits by the non-discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario*), the central value estimate is 1.5¢/kWh of wind; across the remaining three scenarios, the estimated benefit ranges from 0.3¢/kWh of wind (low) to 2.5¢/kWh of wind (high) to 4.7¢/kWh of wind.

Text Box 3-5

Net Energy Requirements for Different Electric Generating Technologies.

Similar in concept to the assessment of life-cycle GHG emissions is the aim of a large body of literature to estimate on a life-cycle basis the amount of energy required to manufacture and operate energy conversion technologies or fuels (i.e., "input" energy). This concept helps inform decision makers on the degree to which various energy technologies provide a "net" increase in energy supply, and is often expressed in the form of either:

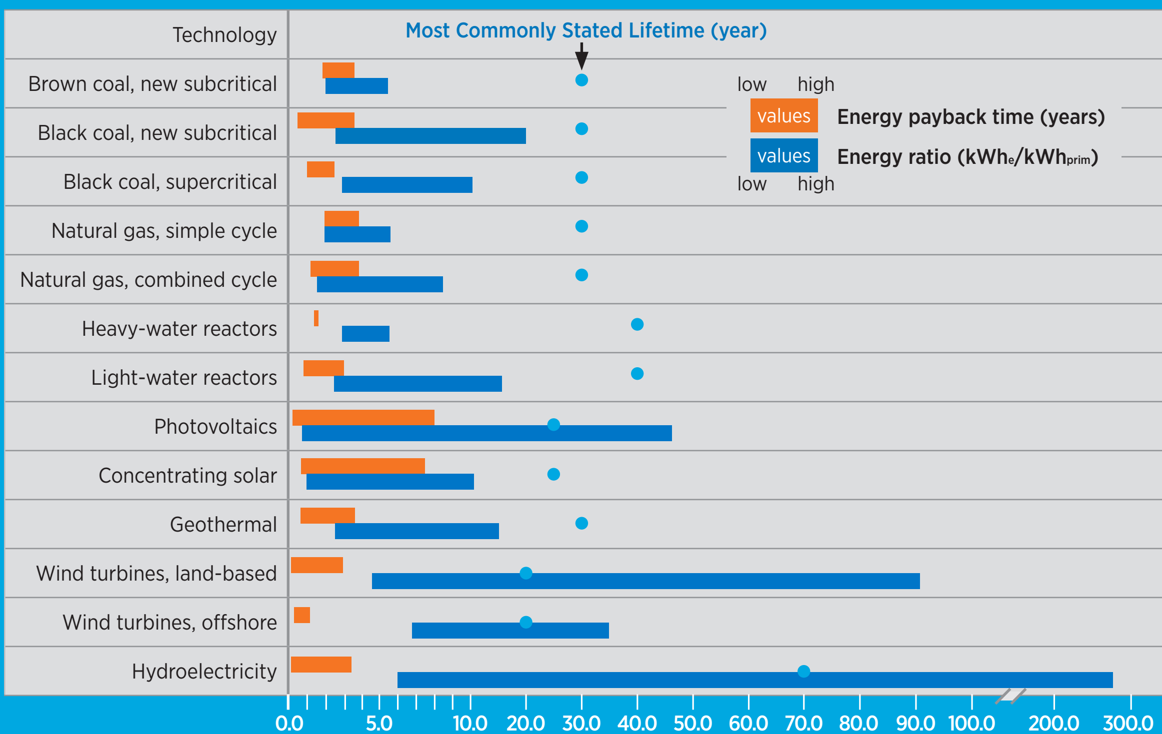
- **Energy ratio:** a ratio of the amount of energy produced by a technology over its lifetime to its input energy; or
- **Energy payback time:** the amount of time required to pay back the input energy given the amount of yearly energy produced.

This text box summarizes published estimates of these two metrics for wind technologies, in comparison to estimates for other electric generation technologies as presented in a recent report from the Intergovernmental Panel on Climate Change [132]. With regard to wind energy, 55 references reporting more than 130 net energy estimates were reviewed, using the same literature screening approach as for the review of life-cycle GHG emissions (see Appendix J).

The figure presents a summary of the review. To be clear, these results are reported from studies that exhibit considerable methodological variability. Although previous work has identified several key issues that can influence results (e.g., [133, 134, 135]), the literature remains diverse and unconsolidated. Variability in the results for wind, for example, may in part be due to difference in the treatment of end-of-life modeling (e.g., recycling); assumed system lifetime and capacity factor; technology evaluated (turbine size, height); and whether turbine replacement is considered.

Notwithstanding these caveats, the results suggest that both land-based and offshore wind power have similar, if not somewhat lower, energy payback times as other technologies, with higher (especially at the high end) energy ratios. That is, wind energy performs relatively well in comparison to other electric generation technologies on these metrics, requiring roughly the same or even lower amounts of input energy relative to energy produced.

Review of energy payback and energy ratios of electricity generating technologies



Note: Energy ratio is the ratio of energy produced by a technology over its lifetime to the input energy required to build the power generating technology. Energy payback time is the amount of time required to pay back the technology's input energy requirements given the amount of yearly energy produced

Source: Non-wind estimates from [132]; wind estimates based on literature review detailed in Appendix J.

3.8 Air Pollution Impacts

Using wind energy to offset the use of fossil generation brings potential public health and environmental benefits. The health, environmental, and ecosystem impacts of electricity supply are far reaching, with every energy source having some impact in terms of air pollutants, water pollutants, land use and degradation, and waste generation and disposal. A thorough review of all types of impacts is beyond the scope of the *Wind Vision*, but reviews can be found elsewhere [132, 136, 137, 138]. The *Wind Vision* analysis focuses on air pollutant emissions. This is because the costs to society of air pollutant emissions are significant, and are often much higher than some other environmental impacts of energy supply [132].

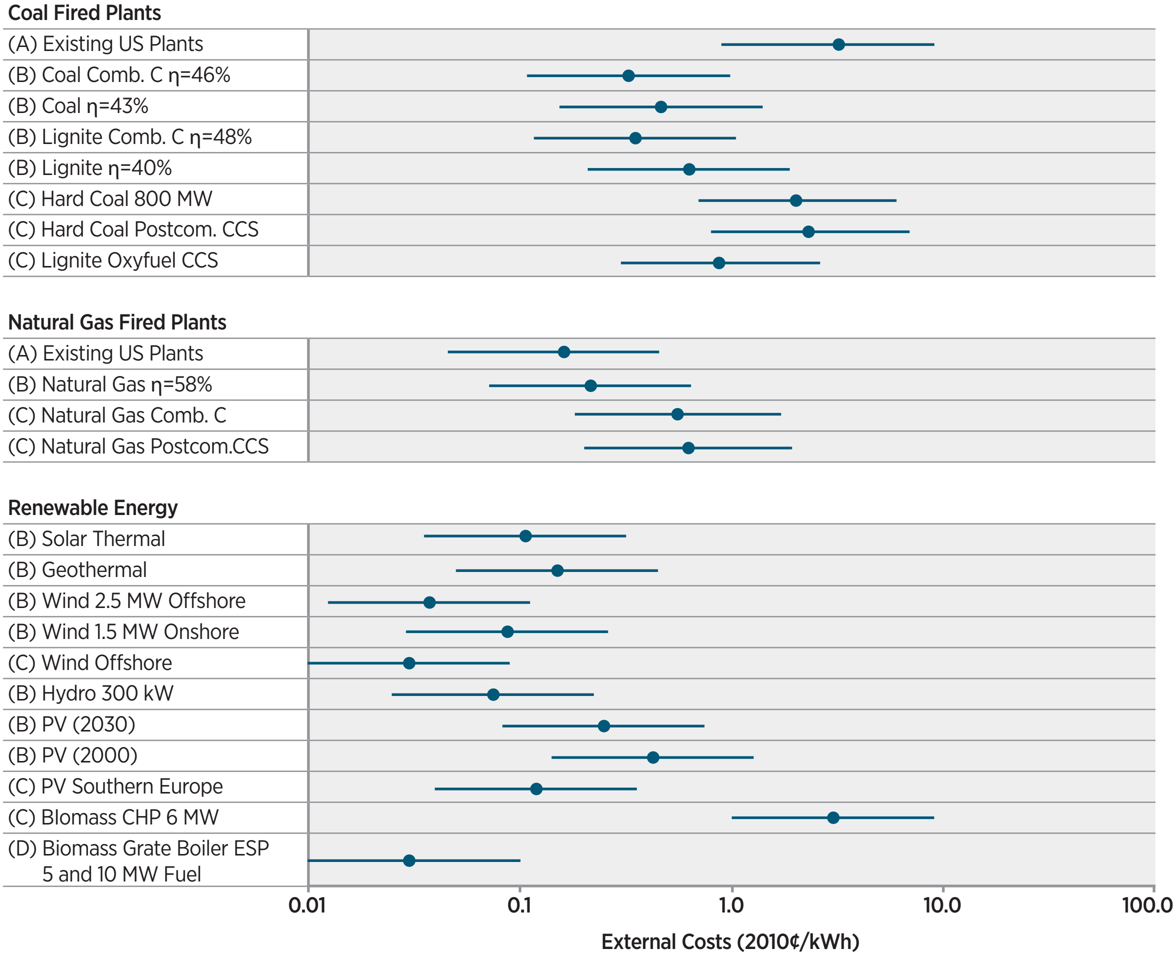
Turconi et al. [139] and Edenhofer et al. [132] reviewed published estimates of air pollutant emissions from electricity generation technologies. Emissions were considered across the life-cycle of each technology—from those associated with extraction and processing of fuels, to manufacture and construction of generation facilities, to operation of those facilities and their end-of-life decommissioning. In short, these meta-studies find consistent evidence that, on a life-cycle basis, wind has very low air pollutant emissions as compared to fossil fuels.

Estimating the impact of different energy technologies on the health of ecosystems and humans, and then quantifying those impacts in monetary terms, is challenging. Nonetheless, several major studies have been conducted in the European context to estimate these so-called “externalities” [146, 147, 148], and one prominent study for the United States was completed by the National Research Council (NRC) in 2010 [138]. Figure 3-33 displays the range of results from some of these studies, focusing on damages from air pollutants. It indicates a similar outcome as that for physical emissions: Health-related externalities are much lower for wind than almost any other electric generation technology.

The NRC study’s [138] quantitative damage estimates were restricted to a limited set of air pollutants: particulate matter (PM) [both coarse particles (PM_{10}) and fine particles ($PM_{2.5}$)], SO_2, and NO_X. The monetized adverse effects from these emissions were primarily due to human health outcomes (premature mortality and morbidity), but also included consequences from decreased timber and agriculture yields, reduced visibility, accelerated degradation of materials, and reductions in recreation services. Damages were evaluated from the operation of combustion technologies; for renewable energy technologies, externalities were only discussed qualitatively. The NRC acknowledged significant uncertainty in its assessment, but concluded that the estimated damages should be considered underestimates of true damages given that not all impact pathways were considered.[108] Notwithstanding these caveats, NRC estimated that, in 2005, the emissions from 406 U.S. coal-fired power plants caused aggregate damages of $62 billion (or 3.2¢/kWh) in 2007$, primarily from exposure to PM created from SO_2 emissions [138]. Pollution damages from gas-fueled plants tend to be substantially lower than those from coal plants; the NRC’s sample of 498 gas facilities produced damages in 2005 estimated at $740 million, or 0.16¢/kWh.

More recent research suggests that the NRC study may have substantially understated the health and environmental damages of air pollution emissions. Since the publication of the NRC study in 2010, updated damage estimates have been released [140] that were on average 2–3 times higher than the original values in NRC. Researchers at the EPA have also estimated far greater damages from electricity generation. Fann et al. [141] estimate damages from power plant SO_2 emissions alone to be equivalent to $280 billion in 2005 and $133 billion in 2016 (2010$) in the United States. Machol and Rizk [142], following a similar methodology as developed by Fann et al. [143], estimate total damages from fossil fuel electricity in the United States to equal $361.7–$886.5 billion (2010$) annually. Similarly, Thompson et al. [144] apply EPA-based methods to estimate sizable heath co-benefits from carbon mitigation (see also [145]). The EPA, meanwhile, has applied the methodology presented in Fann et al. [141, 143] on a number of occasions to estimate the benefits of emission reductions from power generation. As a result, the EPA’s Clean

108. Non-quantified impacts included heavy metal releases; radiological releases; waste products, land use, and water quality impacts associated with power and upstream fuel production; noise; aesthetics; and others.



Notes: Figure utilizes a logarithmic scale and is derived from Edenhofer et al. [116]. More specifically, the figure summarizes the results of four prominent externalities studies conducted worldwide ((A) NRC 2010 [138]; (B) Krewitt and Schlomann 2006 [146]; (C) Preiss 2009 [147]; Ricci 2010 [148]; (D) Sippula et al. 2009 [149]). Uncertainty is assumed to be a factor of three. Costs are in 2010¢/kWh. Abbreviations: CCS = carbon capture and storage; Comb.C = combined cycle; Postcom = post-combustion; η = efficiency factor; PV = photovoltaic; CHP = combined head and power; ESP = electrostatic precipitators.

Figure 3-33. Range of health-related costs from air pollutant emissions from electricity generation technologies

Power Plan [92] and other regulatory actions now include larger estimates of the benefits from emissions reductions than those in the NRC study.

This section summarizes the analysis methods used to quantify the air pollution benefits of achieving the *Wind Vision Study Scenario* (see Appendix L for further details on these methods and underlying assumptions). It then presents estimates for the potential air pollutant emissions reductions from the *Study Scenario*, relative to the *Baseline Scenario*, and assesses the health and environmental benefits associated with those potential emissions reductions.[109] Two methods are used to quantify the reduced health and environmental damages of the *Study Scenario* in monetary terms, resulting in three different monetary estimates (EPA includes a “low” and a “high” case). In all cases, only a subset of the potential air pollution benefits of wind energy are evaluated, focused specifically on impacts from SO_2, NO_X, and $PM_{2.5}$ emissions. A brief discussion of an alternate approach to quantifying the air pollution benefits of the *Study Scenario*

109. This section evaluates the impacts of the *Central Study Scenario* and *Baseline Scenario* only. See Section 3.1.3 for detailed explanation of the scenarios. The ranges presented in this section are driven by the range of parameters evaluated and not by the range of scenario results.

is also provided, one in which the benefits derive not from reduced health and environmental damages but instead from reducing the cost of meeting more stringent air pollution regulations.[110]

3.8.1 Methods

This section summarizes the basic methodology used to estimate potential air pollution benefits for the *Study Scenario*. Appendix L more fully describes the assumptions, data sources, and calculations used.

Health benefits are realized when exposure to pollutants is reduced. The estimates used in the *Wind Vision* to calculate these benefits depend on three critical steps: (1) estimation of pollutant emissions from power plants; (2) modeling the atmospheric dispersion and secondary reaction of those pollutants; and (3) estimation of population exposure to primary and secondary pollutants, the exposure-response relationship for specific outcomes (i.e., morbidity or premature mortality), and the monetary quantification of those outcomes.

For step (1), pollutant emission estimates are developed for both the *Study Scenario* and the *Baseline Scenario*, and are a function of the product of ReEDS generation outputs (MWh, by generation type and vintage) for both scenarios with assumed emission rates (grams/MWh, by generation type and vintage). The stringency of future air pollution regulations impacts emissions rates (and generation investment and dispatch decisions), and, therefore, also affects estimates of the air pollution benefits of wind energy. For the purpose of this analysis, initial year-one emission rates were estimated based on reported historical plant-level emission rates for SO_2, NO_X, and $PM_{2.5}$, and aggregated to each type of power plant in ReEDS and to each of the 134 ReEDS regions across the contiguous United States. Emission rates were updated over time as plants retire, under the assumption that the Mercury and Air Toxics Standards (MATS) are implemented in 2016, and as limited by the Cross-States Air Pollution Rule (CSAPR) starting in 2014. The MATS requirements, in particular, significantly limit SO_2 emission rates.

As discussed in Section 3.7, increased reliance on variable wind generation will require fossil plants to operate in a more flexible manner, potentially increasing the air pollution emissions from those plants on a per-MWh basis (e.g., [150]). This may create an emissions penalty relative to a fully loaded plant [102]. Though the *Wind Vision* analysis does not capture these effects, research results suggest that emissions are reduced by wind energy, even after accounting for any emissions penalties [73, 109, 151]. In a 2013 analysis of this issue, Lew et al. [65] find that accounting for emissions impacts related to increased coal plant cycling slightly improves (by 1–2%) the avoided NO_X emissions of wind and solar relative to the avoided emissions, based on an assumption of a fully loaded plant. This result is driven by average emissions rates of coal plants decreasing during times when the plants are part-loaded. Conversely, that study finds that accounting for cycling impacts on SO_2 emissions reduces the avoided SO_2 emissions of wind and solar by 3–6% relative to avoided emissions based on an assumption of a fully loaded plant. A similarly detailed analysis of avoided NO_X and SO_2 emissions with wind and solar in the mid-Atlantic region reports more substantial emissions penalties, in part due to frequent cycling of supercritical coal plants [73]. In both cases, however, the impacts are not large enough to dramatically alter the basic results reported here. Further research is warranted to quantify emissions penalties related to cycling and to identify strategies for mitigating those emissions.

For steps (2) and (3), this analysis depends on previous estimates of pollutant dispersion and reaction, exposure and response, and monetary damage assessment. Two different approaches are used, resulting in three estimates. The first method is as applied by the EPA, most recently in its 2014 Regulatory Impact Analysis for the Clean Power Plan [92]. EPA applied two different sets of estimates for the average benefit per ton of reduced SO_2, NO_X, and $PM_{2.5}$ emissions from power plants across three broad regions on the United States, resulting in an "EPA-low" and an "EPA-high" estimate of the benefits of the *Study Scenario*. As an alternative to the EPA estimates, we use benefit-per-ton estimates from the Air Pollution Emission Experiments and Policy analysis model version 2 (originally APEEP, now abbreviated AP2), also for SO_2, NO_X, and $PM_{2.5}$. The AP2 model was used in the 2010 NRC study [138] discussed previously,

110. Basic economics demonstrate it is more cost-effective to address unpriced environmental effects directly through, e.g., environmental taxes or cap-and-trade, rather than through technology- or sector-specific incentives [117]. Also, conceptually, additional welfare benefits from pollution reduction can only occur if these direct environmental regulations have not already been established at the optimal welfare maximizing level [50, 101, 102].

as well as by Siler-Evans et al. [99] to estimate the benefits of wind and solar energy in reducing the health and environmental damages from existing power plants from 2009 to 2011.[111]

Both EPA (low and high) and AP2 develop benefit-per-ton estimates by combining air quality modeling with exposure modeling, exposure-response relationships, and monetary damage estimates. There are, however, significant differences in air quality modeling methodology between EPA and AP2; in the assumed relationship between exposure and impact between EPA-low, EPA-high, and AP2; and in the specific health and environmental impacts assessed. The result is three distinct monetary estimates of the reduced air pollution damages associated with the *Study Scenario* relative to the *Baseline Scenario*.

In addition to estimating the air pollution benefits of the *Study Scenario*, this analysis also presents an alternate approach to quantifying air pollution benefits. This alternative approach assumes the presence of binding cap-and-trade programs limiting air pollution, and focuses on the ability of wind to potentially offset the cost of meeting those air pollution regulations. Details are provided in the next section.

Overall, the basic approaches described above have been commonly used to quantify the benefits of renewable energy. Siler-Evans et al. [99], for example, used AP2 to estimate the health and environmental benefits of wind and solar energy. Additionally, to account for the possibility of binding cap-and-trade programs, Siler-Evans et al. [99] developed a benefit estimate in which wind generation does not decrease air pollutant emissions for capped pollutants in locations where the cap-and-trade governs, but rather principally avoids costs associated with the implementation of other pollution control strategies. Several studies [98, 100, 101] also quantify the benefits of renewable energy due to reduced air pollution damages. Heeter et al. [153] find that state-level studies of the benefits and costs of RPS policies sometimes use either damage-based or compliance cost-based approaches to quantify air pollution impacts. Finally, Bolinger and Wiser [154] report that electric utilities sometimes consider future air pollution regulations and associated compliance costs when selecting among alternative energy resource portfolios.

3.8.2 Air Pollution Benefits of Wind Energy

Achieving the *Study Scenario* will provide air pollution benefits, relative to the *Baseline Scenario* in which no additional growth in wind capacity is assumed to occur. Considerable uncertainty exists about the magnitude of these benefits, however, including uncertainties driven by the representation of future air pollution regulations, air pollutant transport assumptions that connect emissions to concentrations, assumptions about the future such as population and income growth, and the translation of emission concentrations to impacts and monetary quantification.

Figure 3-34 illustrates potential electric-sector air emissions for the *Study Scenario* and *Baseline Scenario*. On a national basis, emissions of SO_2, NO_X, and $PM_{2.5}$ are shown to be lower in the *Study Scenario*. Specifically, on a cumulative basis, the *Study Scenario* has estimated emissions reductions from 2013 to 2050 (relative to the *Baseline Scenario*) of 2.6 million metric tonnes of SO_2, 4.7 million metric tonnes of NO_X, and 0.5 million metric tonnes of $PM_{2.5}$.

An important feature of the data in Figure 3-34 is the precipitous drop of SO_2 emissions from 2010 through 2016 in both scenarios. This decline is due to the assumed implementation of MATS, which requires that all (new and existing) coal plants meet acid gas (such as SO_2 or hydrogen chloride), PM and other pollutant emission-rate limits. Note that MATS is modeled outside of ReEDS, as a post-processing step; see Appendix L for further details. Aside from this dramatic change to SO_2 emissions, emissions of all three pollutants are relatively stable until 2040, when they are projected to decline by half over the course of a decade as a result of a drop in coal generation. This is due in part to additional coal plant retirements.

111. One important value used to generate the monetary benefit estimates is the value of a statistical life assumed for mortality damages. The AP2 analysis assumes that the cost of premature deaths is $6 million (in 2000$), regardless of age, which is consistent with the value used by the NRC [138] and Siler-Evans et al. [99]. This cost is also near the mid-point of available literature estimates, and is in line with value of statistical life assumptions used by the EPA in regulatory impact analyses (e.g., [152]). The EPA-based analysis assumes that the cost of premature deaths is $6.3 billion (in 2000$, adjusted for currency inflation and income growth). Note that the EPA provides benefit estimates that increase in the future with population and income growth. For the *Wind Vision*, damages from AP2 are scaled over time based on U.S. Census Bureau population projections and are based on per capita income growth projections used by EIA [4], using an elasticity of the value of statistical life to income growth consistent with NRC [138].

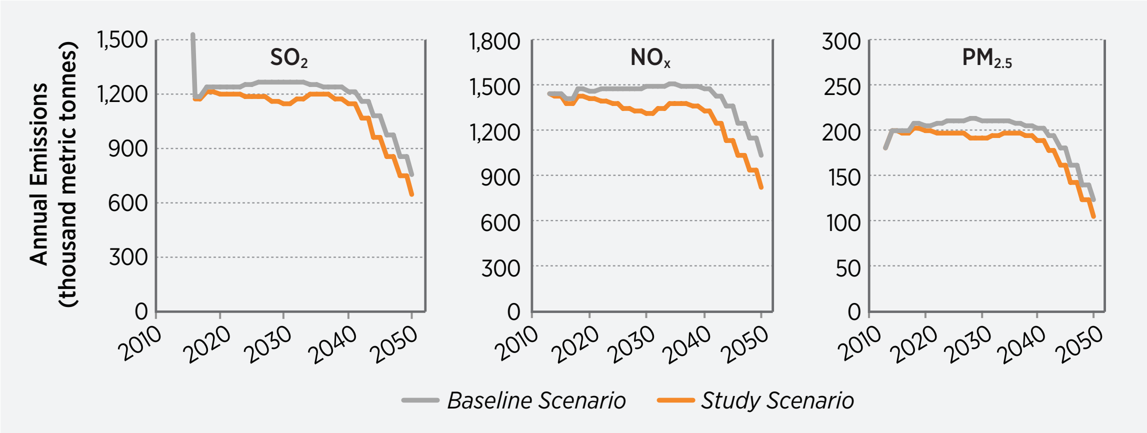


Figure 3-34. Electric sector SO_2, NO_X, and $PM_{2.5}$ emissions in *Study* and *Baseline Scenarios*

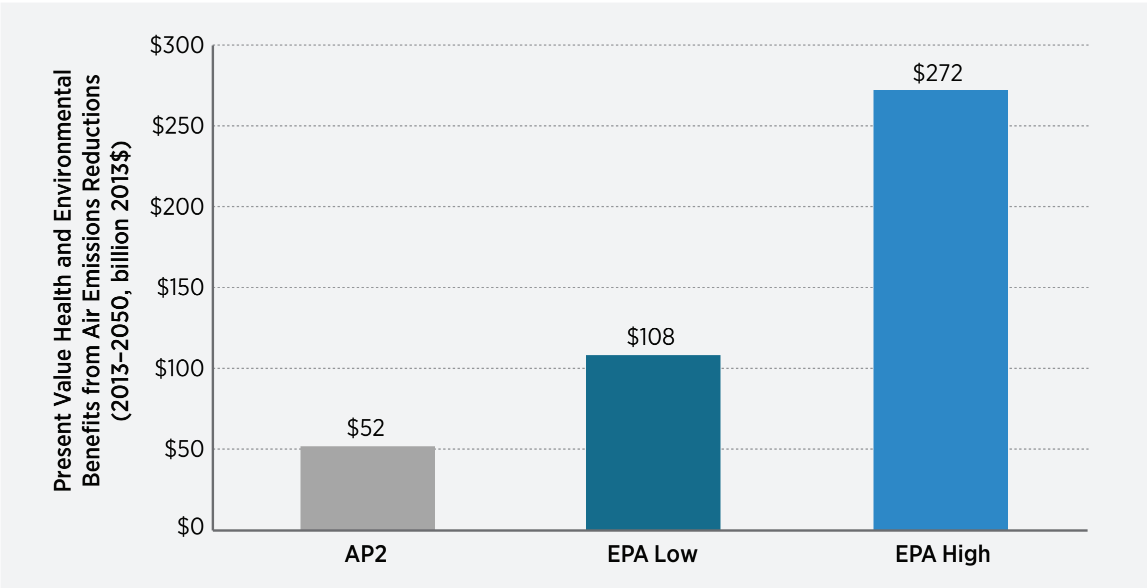


Figure 3-35. Estimated benefits of the *Study Scenario* due to reduced SO_2, NO_X, and $PM_{2.5}$ emissions

Based on these SO_2, NO_X, and $PM_{2.5}$ emissions reductions, Figure 3-35 summarizes the estimated present value of the air pollution benefits of the *Study Scenario* (relative to the *Baseline Scenario*), applying the methods described previously and detailed in Appendix L. Discounted, present value air pollution benefits are estimated at $52 billion, $108 billion, and $272 billion under AP2, EPA-low, and EPA-high respectively (3% discount rate, 2013–2050).[112,113] To put these figures in another context, they are equivalent to an average levelized benefit of 0.4¢/kWh of wind, 0.9¢/kWh of wind, and 2.2¢/kWh of wind.[114]

The range of benefit estimates that exists between EPA-low ($108 billion) and EPA-high ($272 billion) is due to uncertainty in the epidemiology that connects pollution exposure to health consequences. EPA-low is based on research summarized in Krewski et al. [155] and Bell et al. [156], whereas EPA-high is based on research presented in Lepeule et al. [157] and Levy et al. [158]. Both sets of epidemiology research have different strengths and weakness and EPA does not favor one result over the other; see Appendix L for more information.

The lower AP2 estimate ($52 billion) relies on epidemiology assumptions consistent with EPA-low, but applies different air quality and meteorological modeling techniques. This drives the differences between AP2 and EPA-low. Both sets of air quality modeling techniques have advantages and disadvantages vs. one another; a description of these differences is provided in Appendix L. One difference between EPA and AP2 relates to the specific health and environmental impacts considered. In this instance, however, the differences would—all else being equal—deflate the EPA estimates relative to AP2. In particular, both AP2 and EPA consider many of the health (mortality and morbidity) consequences of SO_2, NO_X, and $PM_{2.5}$ emissions, but the specific impact pathways differ somewhat. As one example, AP2 includes primary pollutant exposure as well as secondary exposure to ozone during the ozone season and to secondary $PM_{2.5}$ that derives from directly emitted SO_2 and NO_X. EPA, on the other hand, does not include primary exposure to SO_2 and NO_X, focusing instead entirely on secondary particulate matter and ozone exposure. Unlike EPA, AP2 also includes consequences from decreased timber and agriculture yields, reduced visibility, accelerated degradation of materials, and reductions in recreation services. These differences in quantified impact pathways imply that the AP2 results are somewhat more inclusive. The majority of the damages derive from mortality and morbidity from primary and secondary $PM_{2.5}$ and ozone exposure [140, 159], however, and the differences between AP2 and EPA on this score are minor. Further discussion of the differences between AP2 (and, previously, APEEP) and EPA are highlighted in Fann et al [141], Machol and Rizk [142], and Brown et al. [160].

Table 3-5 provides additional detail on these monetary estimates over the entire 2013–2050 analysis period and, for the EPA-derived figures, also lists in some detail the estimated health (mortality and morbidity) benefits from the *Study Scenario*. Overall, the majority of the monetary benefits derive from reduced levels of premature mortality associated with the *Study Scenario*. Focusing on the EPA-low estimate, because it is in the middle of the range of estimates presented, the *Study Scenario* is found to result in nearly 22,000 fewer premature mortalities than the *Baseline Scenario* over the 2013–2050 timeframe. Though the monetary benefit is smaller, a large number of additional morbidity benefits are

112. Though the emission rate estimates developed outside of the ReEDS model and applied in this section include a representation of MATS, the ReEDS generation estimates do not include MATS. They instead include a representation of a SO_2 cap-and-trade system; the core ReEDS results were not updated to include MATS because MATS was under legal challenge at the time the scenario approach was finalized. Preliminary analysis suggests that the *Wind Vision* air quality benefit estimates presented here would increase by at least 20–30% if ReEDS were updated to account for the new regulatory environment, with potentially even-greater benefits depending on how the new environment is represented. The benefit increase would be seen as the SO_2 cap-and-trade system would become non-binding in most years due to the emission controls required by MATS. On the other hand, representation of another recent proposed change to the regulatory environment, the EPA's Clean Power Plan, would likely reduce future estimates of air quality benefits. At the time of this publication, the status of MATS remains in legal review pending a decision by the U.S. Supreme Court. See Appendix L for more details.

113. Annual benefits reflecting yearly avoided emissions are as follows: (1) **AP2:** $0.9 billion (2020), $4.3 billion (2030), $4.8 billion (2050); (2) **EPA-low:** $2.4 billion (2020), $8.3 billion (2030), $10.1 billion (2050); (3) **EPA-high:** $5.6 billion (2020), $20.3 billion (2030), $27.4 billion (2050) [2013$].

114. These **levelized** impacts are calculated by dividing the discounted benefits by the discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario.* When instead presented on a **discounted,** average basis (dividing discounted benefits by the non-discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario*), the values are 0.2¢/kWh of wind, 0.4¢/kWh of wind, and 1.0¢/kWh of wind.

Table 3-5. Accumulated Emissions, Monetized Benefits, and Mortality and Morbidity Benefits over 2013–2050 for the *Study Scenario* Relative to the *Baseline Scenario*

Impacts	SO_2	NO_X	$PM_{2.5}$	Total
Emissions Reductions				
Central Study Scenario air pollution reduction (million metric tonnes)	2.6	4.7	0.5	—
Total Monetized Benefits (Present Value)				
EPA-low benefits (billion 2013$)	71	28	9	108
EPA-high benefits (billion 2013$)	174	78	21	272
AP2 benefits (billion 2013$)[a]	24	19	8	52
EPA Total Mortality Reductions				
EPA-low mortality reductions (count)	14,400	5,500	1,900	21,700
EPA-high mortality reductions (count)	29,100	15,200	4,300	48,700
EPA Morbidity Reductions from Primary and Secondary $PM_{2.5}$ Impacts				
Emergency department visits for asthma (all ages)	7,000	2,200	900	10,100
Acute bronchitis (age 8–12)	18,800	5,500	2,500	26,800
Lower respiratory symptoms (age 7–14)	242,200	69,900	31,900	344,000
Upper respiratory symptoms (asthmatics age 9–11)	383,000	111,600	45,600	540,200
Minor restricted-activity days (age 18–65)	9,118,000	2,685,800	1,243,000	13,046,600
Lost work days (age 18–65)	1,525,800	462,900	2,040,008	2,192,700
Asthma exacerbation (age 6–18)	858,800	104,300	47,700	1,010,800
Hospital admissions, respiratory (all ages)	5,000	1,400	600	7,000
Hospital admissions, cardiovascular (age > 18)	5,400	1,800	700	7,900
Non-fatal heart attacks (Peters et al. 2001)	17,700	5,400	2,300	25,300
Non-fatal heart attacks (pooled estimates—4 studies)	2,000	600	200	2,800
Morbidity Reductions from NO_X → Ozone Impacts				
Hospital admissions, respiratory (ages > 65)	—	9,200	—	9,200
Hospital admissions, respiratory (ages < 2)	—	2,800	—	2,800
Emergency room visits, respiratory (all ages)	—	3,800	—	3,800
Acute respiratory symptoms (ages 18–65)	—	5,882,000	—	5,882,000
School loss days	—	2,459,600	—	2,459,600

Note: Monetized benefits are discounted at 3%, but mortality and morbidity values are simply accumulated over the 2013–2050 time period. EPA benefits derive from mortality and morbidity estimates based on population exposure to direct emissions of $PM_{2.5}$ and secondary $PM_{2.5}$ (from SO_2 and NO_X emissions), as well as ozone exposure from NO_X emissions during the ozone season (May–September). Primary and secondary $PM_{2.5}$ effects account for approximately 90% of the mortalities and monetized benefits in both the high and low cases.

a. AP2 benefits are derived from mortality and morbidity estimates based on population exposure to direct emissions of $PM_{2.5}$, SO_2 and NO_X, and secondary $PM_{2.5}$ (from SO_2 and NO_X emissions), as well as ozone exposure from NO_X emissions during the ozone season (May–September). AP2 benefits also include consequences from decreased timber and agriculture yields, reduced visibility, accelerated degradation of materials, and reductions in recreation services.

also associated with the *Study Scenario*, as detailed in Table 3-5. For example, the *Study Scenario* is estimated to lead to ~41,000 fewer visits to the emergency department or hospital due to cardiovascular, respiratory, or asthma symptoms. The improved air quality in the *Study Scenario* is also estimated to result in ~2.2 million fewer lost work days.

Under the EPA-low case, 66% of estimated monetary benefits are derived from reductions in SO_2 emissions. Reductions in NO_X emissions account for 26% of the monetary benefits in the EPA-low case. Reductions in direct $PM_{2.5}$ emissions account for 8% of the benefits.

Consistent with the results from Siler-Evans et al. [99] and NRC [138], a large majority (>95%) of these health benefits are found to be concentrated in the eastern half of the United States, especially in areas where air pollution from coal plants predominates. Benefits in the western United States are limited due, in part, to lower overall emissions in those areas and to lower population densities.

As noted earlier, there is an alternate approach to valuing emission reductions in the case that binding cap-and-trade regulations exist. This approach reflects the fact that the design of air pollution regulations can impact not only the size but also the nature of the benefit derived from wind energy. In particular, when cap-and-trade programs are used to limit air pollution (as under the Clean Air Interstate Rule and CSAPR for SO_2, NO_X, and in some regions of the United States), and if those caps are strictly binding over time, increased wind energy may not reduce capped pollution emissions because the potential avoided emissions from wind may be offset by increases in emissions elsewhere as allowed under the cap [99, 101]. In this case, the benefits of increased wind energy derive not from reduced health and environmental damages, but instead from reducing the cost of complying with the air pollution regulations, as determined by pollution allowance prices.[115]

Though cap-and-trade programs currently exist in various regions of the United States for both SO_2 and NO_X, those programs have not been fully binding [162, 163]. Assessment of the *Study Scenario* and *Baseline Scenario* suggests that the CSAPR caps are unlikely to be strongly binding in the presence of MATS. The benefits of the *Study Scenario,* therefore, are not estimated from the perspective of reducing pollution regulation compliance costs. This alternative valuation approach is provided, however, because it is possible that future national or regional cap-and-trade regulations could impact the size and nature of the benefits from the *Study Scenario*. Whether any such resulting benefits are lower or higher than those health and environmental benefits presented here would depend on the stringency of the presumed cap and the resulting projected cost of pollution allowances. Due to a lack of ability to forecast the presence of future regulations and their stringency, this valuation approach is not applied here. With MATS, it is less likely that a binding cap-and-trade program for SO_2 emissions would be established in future years. For comparison purposes, however, note that EPA-estimated SO_2 allowance prices under the CSAPR (before MATS was proposed) [164] were roughly 1/40th the monetized health benefits value estimated in EPA [92], and that historical SO_2 and NO_X allowance prices have similarly been well below health-based estimates. As such, it is possible under binding cap-and-trade policies that the air emissions benefits of wind energy would be lower than otherwise presented earlier in this section.

Overall, the air pollution benefits of the *Study Scenario*, relative to the *Baseline Scenario* in which no new wind is added, are estimated to be sizable but uncertain. The range presented here of $52–$272 billion reflects some, but not all, of that uncertainty, as discussed in more depth in EPA [92]. At the same time, the health and environmental impact pathways analyzed here include only a subset of the impacts associated with SO_2, NO_X, and $PM_{2.5}$, and exclude any benefits associated with reductions in heavy metal releases, radiological releases, waste products, water quality impacts, and many others. If these additional impact pathways were able to be quantified, benefits estimates would increase.[116]

115. Pollution allowance prices represent the marginal cost of complying with a cap-and-trade program. These prices embed the cost of reducing air emissions, whether through the installation of pollution control technologies, fuel switching, or altered generation dispatch. Under a binding pollution cap, wind energy effectively reduces these costs by offsetting fossil generation and helping to meet the emissions cap. Thus, pollution allowance prices may be used to estimate the savings of not needing to pay for compliance.

116. The subset of benefits analyzed here likely represents the majority of the value, because reductions in premature mortality have a high valuation relative to other potential benefits and are strongly associated to reductions to ambient $PM_{2.5}$ concentrations (i.e., linked to reductions in SO_2, NO_X, and $PM_{2.5}$ emissions).

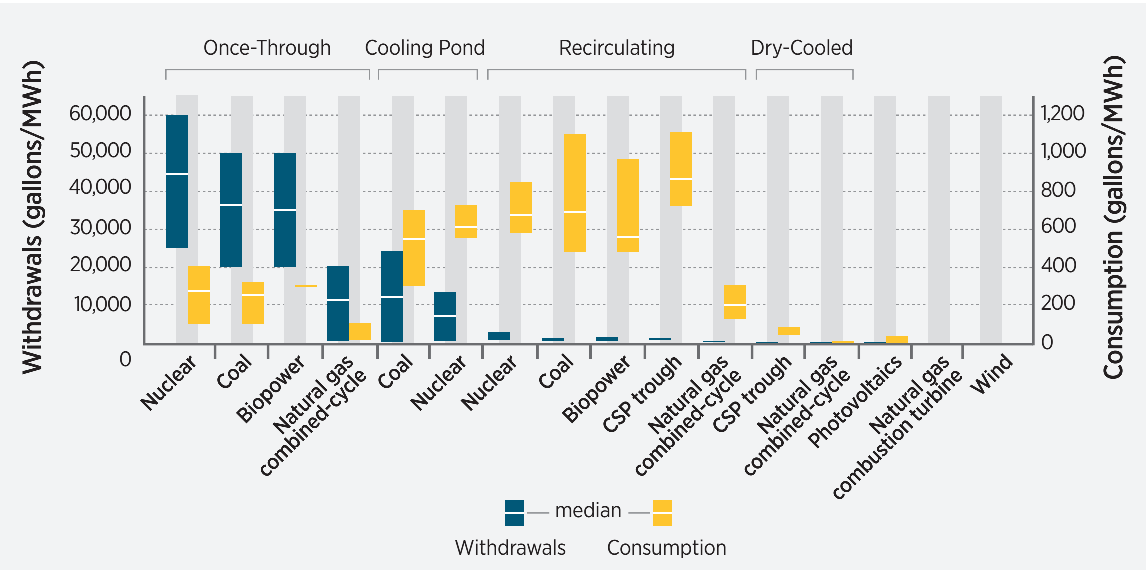
3.9 Water Usage Reduction

Water usage is evaluated based on two key metrics: withdrawal and consumption. Water withdrawal is the amount of water removed from the ground or diverted from a water source for use, but then returned to the source, often at a higher temperature; water consumption is the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment [165]. The U.S. electric sector is the largest *withdrawer* of freshwater in the nation; it accounted for 41% of all withdrawals in 2005 [165]. Freshwater *consumption* from the electric sector represents a much smaller fraction of the national total (3%), but can be regionally important [166, 167].

The primary water demand for the electric sector, both withdrawal and consumption, is for plant cooling. Approximately 80% of the electricity generated in the United States uses a thermodynamic cycle that requires water for cooling [168]. Consequently, the electricity sector both impacts and is highly dependent on water resources [169, 170, 171, 172, 173]. Power plants have sometimes been forced to curtail generation or shut down due to water-related restrictions, in some cases creating electric reliability challenges [174, 175].

The future development of the electric sector will be influenced by water availability, which can affect what types of power plants and cooling systems are built and where those plants are sited. Some proposed power plants have been canceled or had to change locations or cooling systems as a result of water-related restrictions [174]. Water-related operational and siting vulnerabilities could be exacerbated by future changes in the climate, which could alter the spatial and temporal distribution of freshwater resources, water temperatures, and power plant efficiencies [86, 175].

Operational water use requirements can vary greatly depending on fuel type, power plant type, and cooling system, with wind power requiring the lowest amount of water [176]. Figure 3-36 highlights water withdrawal and consumption rates for a variety of power plant types and cooling systems. As shown, thermal power plants using once-through cooling withdraw more water per MWh of electricity than do plants using recirculating cooling systems. Once-through cooling has lower water consumption demands, however, than recirculating systems. Dry cooling can be used to reduce both water withdrawal and consumption for thermal plants, but at a cost and



Source: Averyt et al. [174]

Figure 3-36. Water use rates for various types of power plants efficiency penalty [177]. Non-thermal renewable energy technologies, such as wind and PV, do not require water for cooling and thus have very low water use intensities. Wind power plants require effectively no water for operations, while PV can use a relatively small amount, primarily for washing panels.

In addition to water required for plant cooling and other operations, water may also be needed in the fuel cycle, in equipment manufacturing, and in construction [178, 179]. On a life-cycle basis, thermoelectric water withdrawals and consumption during plant operations are orders of magnitude greater than these other demands [179]; as such, this section focuses on operational water requirements. However, as discussed in Averyt et al. [174], these additional fuel-cycle water demands can have important water quality implications due to, for example, water used in mining, coal washing, and hydraulic fracturing.

Given its low water use intensity, wind energy has the potential to reduce water impacts and water-related vulnerabilities in the U.S. electric sector, potentially providing economic and environmental benefits. Some states (e.g., California, New York) have already proposed measures to reduce the water intensity of the electricity produced in their states (California State Lands Commission 2006; New York State Department of Environmental Conservation 2010). The EPA has also invoked the Clean Water Act to propose various measures to limit the impacts of thermal power plant cooling on aquatic habitats [180]. To the extent that wind deployment can reduce electric sector water demands, it might also reduce the cost of meeting future policies intended to manage water usage.

This section evaluates the potential operational water withdrawal and consumption reductions associated with the *Study Scenario* compared to the *Baseline Scenario*.[117] National water impacts were evaluated, including by fuel and cooling system type. Because water resources are managed locally and regional trends can differ substantially from national trends, regional water impacts are also presented. Finally, the potential economic and environmental benefits of water use reductions are explored.

3.9.1 Wind Energy Reduces National Water Usage[118]

Meeting the wind deployment levels of the *Study Scenario* is estimated to reduce national electric sector water use, both in comparison to recent use and in comparison with the *Baseline Scenario* in which no additional growth in wind capacity is assumed to occur.

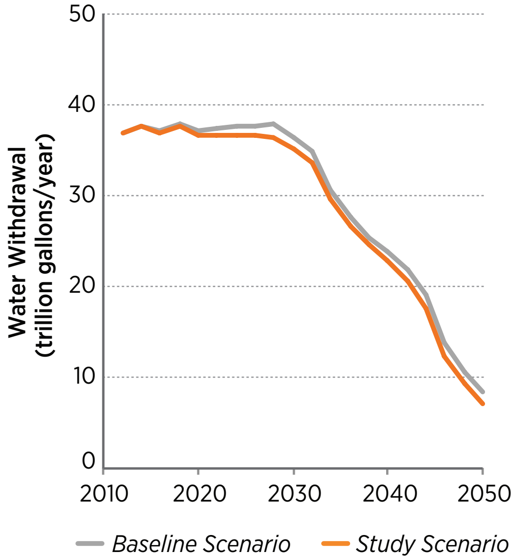
Figure 3-37 shows the decline in annual electric sector water withdrawals for the *Study Scenario* and *Baseline Scenario*, based on ReEDS output, as well as by fuel and cooling system type. On a national level, withdrawals are estimated to decline substantially over time under both the *Study Scenario* and the *Baseline Scenario*. This is largely due to the retirement and reduced operations of once-through cooled facilities and the assumed replacement of those plants with newer, less water-intensive generation and cooling technologies.[119] In the *Baseline Scenario*, once-through cooled plants are largely replaced by new thermal plants utilizing recirculating cooling. In the *Study Scenario*, water-intensive plants are replaced by new, less water-intensive thermal power plants as well as by wind energy, driving somewhat greater reductions in water withdrawals. As a result, national electric sector water withdrawals decline by 1% in 2020 (0.4 trillion gallons), 4% in 2030 (1.3 trillion gallons), and 15% in 2050 (1.3 trillion gallons) in the *Study Scenario* relative to the *Baseline Scenario*.

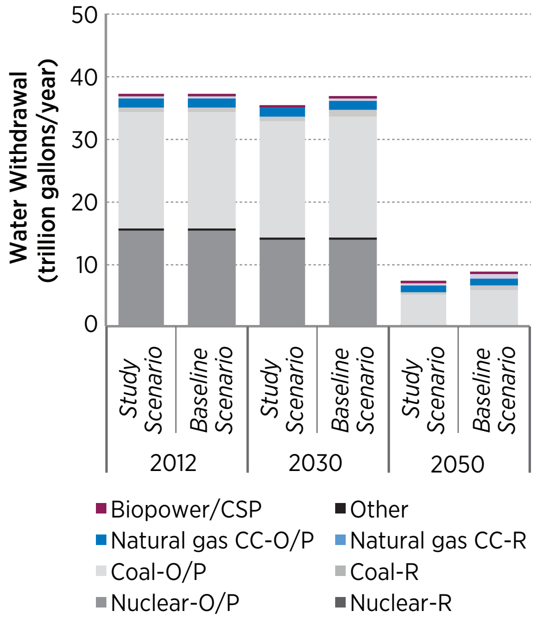
Figure 3-38 shows the change in annual electric sector water consumption for the *Study Scenario* and *Baseline Scenario*, based on ReEDS output, as well by fuel and cooling system type for 2012, 2030, and 2050. Unlike withdrawals, national electric sector water consumption remains higher than 2012 values until after 2040 under the *Baseline Scenario.* It declines after this point, but to a lesser extent than water withdrawals. Consumption decreases sooner and more significantly in the *Study Scenario*. The delayed decrease in water consumption in the *Baseline Scenario* is caused by the assumed replacement of once-through cooled plants with those using recirculating cooling systems (recirculating cooling has higher water consumption). Such cooling system

117. This section evaluates the impacts of the *Study* and *Baseline Scenarios,* under *Central* assumptions only. See Section 3.1.3 for detailed explanation of the scenarios. The ranges presented in this section are driven by the range of parameters evaluated and not by the range of scenario results.

118. Some of the data underlying the figures presented in this section can be found in Appendix K.

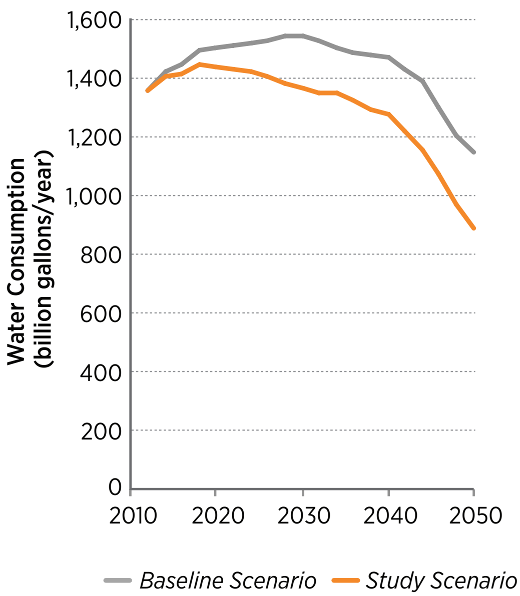
119. Consistent with prior studies and proposed EPA regulations, new power plants in ReEDS are not allowed to employ once-through cooling technologies [170, 172].

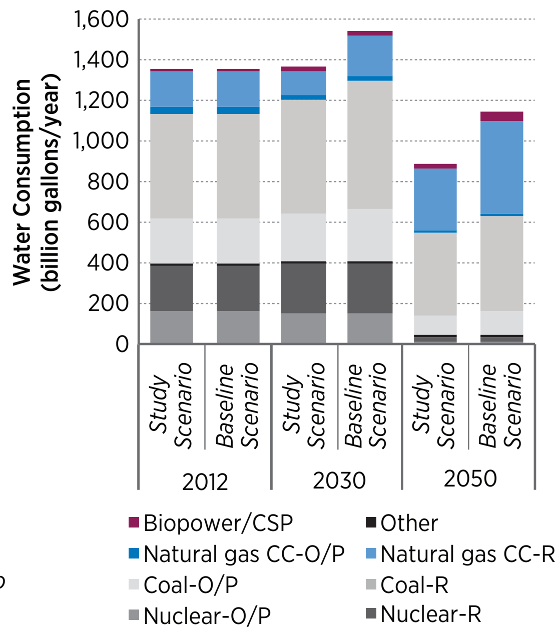




Note: Acronyms used: CSP = concentrating solar power; CC = combined cycle; O/P = once-through or pond cooling system; R = recirculating cooling system.

Figure 3-37. Electric sector water withdrawals for the *Central Study Scenario* and *Baseline Scenarios* (2012–2050), and by fuel type and cooling system





Note: Acronyms used: CSP = concentrating solar power.; CC = combined cycle; O/P = once-through or pond cooling system; R = recirculating cooling system.

Figure 3-38. Electric sector water consumption for the *Study* and *Baseline Scenarios* from 2012 to 2050, and by fuel type and cooling system changes also occur in the *Study Scenario*, but the greater penetration of wind energy reduces water consumption for the sector as a whole. Overall, national electric sector water consumption declines by 4% in 2020 (62 billion gallons), 11% in 2030 (173 billion gallons), and 23% in 2050 (260 billion gallons) in the *Study Scenario* relative to the *Baseline Scenario*. These percentage reductions are greater than for water withdrawals because wind energy is found to generally offset generation that has higher water consumption but lower water withdrawals, e.g., recirculating natural gas combined cycle plants. In comparison to 2012 values, *Study Scenario* consumption is 35% lower in 2050.

These estimates suggest significant potential for wind energy in reducing water use. Water use, however, will be impacted by a variety of changes in the electric sector, such as coal plant retirements, new natural gas combined cycle construction, and, potentially, increased use of dry cooling. These changes may be driven in part by future state and federal water policies, and could affect the estimated water savings of the *Study Scenario*.

3.9.2 Regional Water Usage Trends[120]

Because water resources are managed locally and water is not easily transferred across basins, regional impact analyses can provide critical insight into the sustainability of water use. Because water resource boundaries do not follow state boundaries, analyzing water resource impacts at the watershed level is also useful to water managers. The analysis presented here therefore focuses on 18 defined watershed regions in the contiguous United States.[121]

Figure 3-39 highlights regional percentage changes in water withdrawal in 2050 compared with 2012 for the *Study Scenario* (right) and the *Baseline Scenario* (left). Due to the large estimated reductions in national electric sector water withdrawals over time, all but one of the 18 major watershed regions in the United States experiences reductions in withdrawals in the *Baseline Scenario* from 2012 to 2050, and all regions experience reductions in the *Study Scenario* (there are additional regional increases by 2030; see Appendix K). The degree of estimated water withdrawal reductions varies geographically, with the *Study Scenario* driving somewhat deeper declines by 2050.

More substantial differences between the *Study Scenario* and *Baseline Scenario* are apparent when looking at water consumption. Water consumption declines by 2050 in all but two of the defined watershed regions under the *Study Scenario*; in 11 of 18 regions, consumption reductions are greater than 30% (Figure 3-40). Regional increases under the *Study Scenario* occur in portions of the Southeast and in California. In the Southeast, high withdrawal and low consumption cooling technologies for thermal power plants are assumed to be replaced by low withdrawal and high consumption cooling

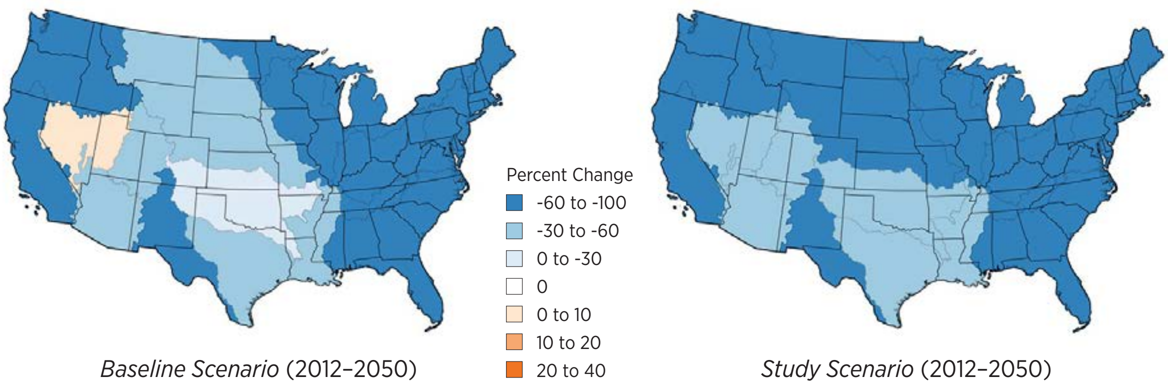


Figure 3-39. Percentage change in water withdrawals in 2050 compared with 2012 for the *Baseline* and *Study Scenarios*

120. Some of the data underlying the figures presented in this section can be found in Appendix K.

121. In particular, water impacts were aggregated from the 134 ReEDS model regions to the two-digit U.S. Geological Survey Hydrologic Unit Code watershed regions, of which there are 18 in the contiguous United States [181]. Data aggregation techniques follow those described in Macknick et al. and Sattler et al. [170, 182].

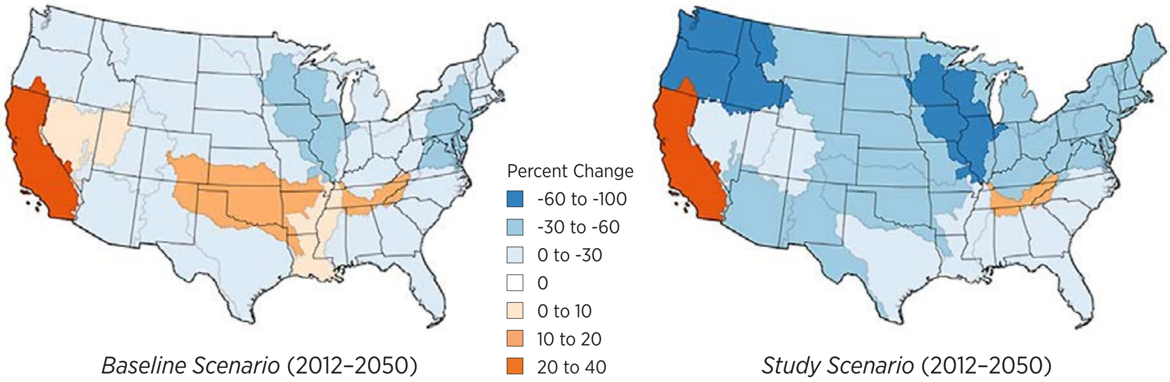


Figure 3-40. Percentage change in water consumption in 2050 compared with 2012 for the *Baseline Scenario* and the *Study Scenario*

technologies, and wind penetration is lower than other regions. In California, increases in consumption are a result of additional recirculating natural gas combined cycle plants and geothermal generation.[122] In the *Baseline Scenario*, five regions experience an increase in consumption by 2050. Specifically, consumption increases in watershed regions covering parts of water-stressed states such as Texas, Oklahoma, New Mexico, Nevada, Utah, and Colorado. The electric sector is not a major contributor to water *consumption* nationally. However, the large potential percentage increases in electric sector water consumption under the *Baseline Scenario* in arid states and regions that, in many cases, already experience water availability issues, could increase regional competition for water resources.[123] Additional maps of water consumption and withdrawal impacts through 2030 are shown in Appendix K.

3.9.3 Economic and Environmental Considerations of Water Use Reduction

The ability of wind energy to reduce water withdrawals and consumption may offer economic and environmental benefits, especially where water is scarce. By reducing electric sector water use, wind energy reduces the vulnerability of electricity supply to the availability or temperature of water, potentially avoiding electric sector reliability events and/or the effects of reduced thermal plant efficiencies. These are concerns that might otherwise grow as the climate changes [175]. Additionally, increased wind deployment might help make available water that could then be used for other productive purposes (e.g., agricultural, industrial, or municipal use), or to strengthen local ecosystems (e.g., benefiting wildlife due to greater water availability). The lower life-cycle water requirements of wind energy can help to alleviate other energy sector impacts to water resource quality and quantity that could occur during fuel production for other technologies, e.g., water used in mining, coal washing, and hydraulic fracturing [174]. Finally, wind deployment might help reduce the cost of future national or state policies intended to limit electric sector water use.

The ReEDS model includes the cost and performance characteristics of different cooling technologies as well as the availability and cost of water supply in its optimization; these costs and considerations are embedded in the results presented earlier. Quantifying in monetary terms any separable, additional benefits from the water use reductions estimated

122. In California, freshwater consumption increases by nearly 50%, largely due to the replacement of once-through cooled facilities along the ocean with power plants utilizing freshwater in recirculating cooling systems. This is consistent with the recommendation of no once-through cooling by the California State Lands Commission (2006).

123. Results in this section were developed using a version of ReEDS that incorporates water availability as a constraint for future development, and model results find that there is sufficient freshwater available in these regions to sustain the model results. However, assumed available water resources include water currently being used for agriculture, which may in practice be difficult to access. In addition, the water availability information used in ReEDS does not take into account all other potential sources of increased water demand, which could further increase competition for scarce resources.

under the *Study Scenario* is difficult, as no standardized methodology exists in the literature to do so. One way to assess the potential economic benefit of water savings is to consider wind deployment as avoiding the *possible* need to otherwise employ thermal power plants with lower water use, or to site power plants where water is available and less costly. To an extent, these costs are already embedded in the ReEDS results, as discussed above. However, water could become scarcer in the future and/or water policy could become stricter, both of which would necessitate additional investments. In such an instance, a possible upper limit of the incremental cost of water associated with conventional thermal generation can be estimated by comparing the cost of traditional wet cooling with the cost of dry cooling. Dry cooling adds capital expense to thermal plants and reduces plant efficiencies. The total cost increase of dry cooling for coal thermal generation has been estimated to be 0.32–0.64¢/kWh [183]. For natural gas combined cycle plants, Maulbetsch and DiFilippo [184] estimate an "effective cost" of saved water at $3.8–$6.8 per 1,000 gallons, corresponding to approximately 0.06–0.17¢/kWh.[124]

These estimated incremental costs for dry cooling are relatively small, and likely set an upper limit on the water-related benefits of wind energy or any other power technology intended, in part, to reduce water usage. The actual benefits would be lower than these figures for a few reasons. First, many regions of the country are not facing water scarcity, so the economic benefits of reduced water use are limited. Second, to the extent that wind offsets more electricity supply (kWh) than electricity capacity (kW), it may not be able to offset the full capital and operating cost of less water-intensive cooling technologies. Third, few plants as of 2013 have been required or chosen to implement dry cooling; alternative, lower-cost means of obtaining and/or reducing water have predominated, including simply locating plants where water is available. Alternative water resources, such as municipal wastewater or shallow brackish groundwater, could also be more cost-effective than dry cooling in some regions [172]. These lower-cost methods of reducing water use are likely to dominate for the foreseeable future. Because of these complicating factors, a separable monetary benefit of the *Study Scenario* in terms of reduced water usage is not estimated.

3.10 Energy Diversity and Risk Reduction[125]

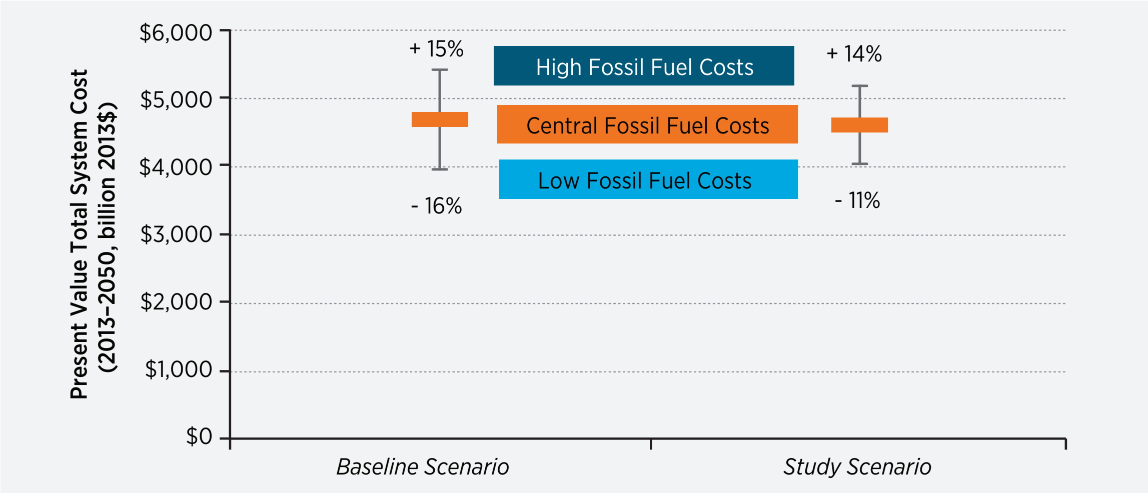
Traditional energy planning focuses on finding least-cost sources of supply. In balancing different electricity supply options, however, the unique risk profiles of each generating source and varying portfolios of multiple generation sources are also considered.

Though wind energy is not free of risk (e.g., due to its variable output and capital-intensive nature), it nevertheless relies on a "fuel" stream that is domestic and is not subject to significant resource exhaustion or price uncertainty. In contrast, fossil generation, and especially natural gas, relies on fuels that have experienced substantial price volatility and for which historical price forecasts have been decidedly poor. As a result, utility-scale wind energy is most often sold through long-term, fixed-price contracts, while fossil generation—and particularly gas-fired generation—is most often sold through short-term contracts and/or at prices that vary with the underlying cost of fuel. In evaluating new generation resources across seven different categories of risk (construction cost, fuel and operating cost, new regulation, carbon price, water constraint, capital shock, and planning risk), Binz et al [185] identified land-based wind as not only one of the lowest cost sources of new generation, but also as one of the lowest risk resources overall.

A variety of methods have been used to assess and sometimes quantify the benefits of fixed-price renewable energy contracts relative to variable-price fossil generation contracts, as well as the benefits of electricity supply diversity more generally. These methods have included the use of risk-adjusted discount rates [186]; Monte Carlo and decision analysis [187]; mean variance-based portfolio theory [188, 189]; market-based assessments of the cost of conventional fuel price hedges [190]; various diversity indices [191, 192]; comparing empirical wind PPA prices to gas price forecasts

124. 2006$ adjusted to 2013$.

125. This section draws heavily on Mai et al. [2].



Note: Central Fossil Fuel Costs reflect the *Central Baseline Scenario* and *Central Study Scenario* modeling inputs; High Fossil Fuel Costs and Low Fossil Fuel Costs reflect *High* and *Low Fossil Fuel Cost Study* and *Baseline Scenarios,* respectively.

Figure 3-41. Electric system cost variability under a range of fuel price scenarios

[193]; and estimating a generation portfolio's sensitivity to high and low fuel prices under high renewable penetration scenarios [194]. Many of these methods have proven to be incomplete or even controversial, and, as a result, a single, standard approach to benefit quantification has not emerged.

Though a full suite of standardized tools for quantifying the myriad risks associated with different electricity resource portfolios is not available, there is broad recognition that the deployment of wind energy can reduce certain risks. In particular, even though natural gas prices and price expectations have declined in recent years, an increase in wind generation mitigates long-term fossil fuel price risks in two ways that *can* be quantified using recognized and—with appropriate caveats—accepted methods. First, by providing electricity purchasers with a long-term fixed-price source of supply (at least when sold under a traditional power sales contract), wind can directly offset the use of fuel streams with variable and uncertain prices, thereby potentially reducing uncertainty in electric system costs. Second, by reducing demand for exhaustible fossil fuels, wind can place downward pressure on fossil fuel prices, with benefits to energy consumers both within and outside of the electricity sector. Though it is acknowledged that these are not the only pertinent areas of risk associated with higher levels of wind generation, the following subsections quantify these two possible impacts, while some of the additional risk mitigation aspects of offshore and distributed wind applications are noted in Section 3.13.[126] Finally, a brief discussion of the competitive and complementary relationship between wind and natural gas is included at the end of this section.

3.10.1 Reducing Uncertainty in Electric System Costs

Figure 3-41 illustrates the sensitivity of total electricity sector costs (on a present value basis) to low and high fuel prices under two scenarios: the *Baseline Scenario* and the *Study Scenario*. In the *Baseline Scenario*, total system costs under *High Fuel Cost* and *Low Fuel Cost* assumptions range from +15% to -16% around the *Central* fuel cost assumptions.[127] Under the *Study Scenario*, the overall range narrows to +14% to -11%.[128]

126. This section primarily evaluates the impacts of the *Study* and *Baseline Scenarios,* under *Central* assumptions. See Section 3.1.3 for detailed explanation of the scenarios.

127. See Section 3.2.4 for a summary of the specific fuel price assumptions used in the *Central, Low Fuel Cost,* and *High Fuel Cost* cases.

128. ReEDS implicitly assumes a cost-plus environment for capacity planning similar to the regulated markets that are common in many, but not all, parts of the United States. This modeling approach is reasonable for this study, as it provides a consistent comparison of the relative economics of different technologies. Some of the nuances involved with competitive wholesale markets, however, are not captured in ReEDS (see Text Box 3-6).

Thus, by replacing gas- and coal-fired generation with wind generation, the *Study Scenario* results in a total portfolio that may be 20% less sensitive to long-term fluctuations in fossil fuel prices.[129] It therefore provides some insurance value against rising costs to consumers due to higher-than-expected fossil fuel prices. Translating this reduced risk into monetary units is not straightforward, however, and would require knowledge about the risk preferences of electricity sellers and purchasers, as well as about the availability, cost, and effectiveness of alternative risk mitigation mechanisms such as forward gas contracts and physical gas supply contracts [190, 194].[130]

The displacement of coal- and gas-fired generation under the *Study Scenario* (relative to the *Baseline Scenario*) also reduces overall demand for coal and natural gas, which in turn can suppress coal and gas prices. This effect results from a shift of the demand curve for fossil fuels along an upward-sloping supply curve,[131] and, while there remains some uncertainty as to the magnitude of the price response, the effect has been both empirically estimated and modeled extensively (e.g., [195]).

Figure 3-42 provides an estimate of this effect using modeling results, showing in particular an increasing reduction over time in natural gas demand and prices under the *Study Scenario*.[132] These gas price reductions are already captured within the ReEDS modeling results presented earlier, but only within the electricity sector, which is just one of the gas-consuming sectors of the overall U.S. economy. If these gas price reductions are applied to AEO Reference Case projections of natural gas consumption *outside* of the electricity sector [4], they yield a present value (from 2013 to 2050 and discounted at a 3% real discount rate) of approximately $280 billion in consumer savings that is not captured within the ReEDS modeling results.

Importantly, these potential price reductions and consumer savings are likely to be primarily or even exclusively *transfer payments* from gas producers and those that benefit from gas production, such as owners of mineral rights (through rents) and governments and taxpayers (through taxes), to gas consumers. As such, the potential for $280 billion in consumer savings outside of the electricity sector, as well as the additional savings captured by ReEDS within the electricity sector, do *not* necessarily reflect a true net increase in aggregate economic wealth. Lower prices for natural gas benefit consumers, at the expense of producers. These significant consumer benefits may, nevertheless, be interesting from a public policy perspective, given that public policy is often formulated with consumers in mind.

It is important to recognize that the gas price reductions shown in Figure 3-42, as well as the $280 billion consumer savings estimate, do not take into account the possibility of a rebound in demand for natural gas outside of the electric sector, spurred by the lower gas prices that result from increasing wind power penetration within the electric sector. ReEDS is an electric sector model, covering only one sector in the broader

129. Moving from a range of +15% to -16% to a range of +14% to -11% is a 20% reduction in sensitivity.

130. Though considered a benefit by many—e.g., recent purchasers of wind power have touted wind's long-term hedge value as an important driver [15, 193]—this reduction in long-term fuel price risk may not be valued as highly (or even at all) by less risk-averse consumers. Furthermore, wind generation is not unique in its ability to reduce fossil fuel price risk, which can also be mitigated through fixed-price fuel contracts or low-cost financial hedges. Physical and financial fuel price hedges, however, are not typically available over long terms, in part due to counterparty risk [193], which is why gas-fired generation in particular is most often contracted only over short terms and/or at prices that vary with fuel costs. This stands in contrast to wind power, which is most often sold over long terms and at prices that are fixed in advance. Finally, the risk reduction shown in Figure 3-41 is measured over the long term. As noted in Text Box 3-6, however, over shorter time durations increased wind penetration may be expected to increase wholesale price volatility due to the variability in wind generation.

131. These supply and demand curves should be thought of as long-term curves reflecting long-term elasticities. Over the short term, price reductions could be even larger, as it will take time for suppliers to restrict supply in response to a reduction in demand (i.e., short-term supply and demand curves are generally thought to be steeper than corresponding long-term curves). Over the long term, supply will have ample time to respond to lower demand, leading to less of a price shift along a flatter supply curve—though not completely flat, since fossil fuels are exhaustible. It is these more enduring long-term price impacts that are of primary interest to this analysis, and that are captured within the ReEDS model. Note that, although ReEDS focuses solely on the electricity sector, it also approximates the long-term supply elasticities that are embedded within the EIA's cross-sector, economy-wide National Energy Modeling System [11].

132. Demand for coal within the electricity sector also declines relative to the *Baseline Scenario,* but the ReEDS model does not project the corresponding impact on coal prices. Because the long-term inverse price elasticity of supply is generally thought to be lower for coal than for natural gas [195], coal price reductions are likely to be muted relative to the gas price reductions shown in Figure 3-42. Further, unlike natural gas, coal is not widely used in the United States outside of the electricity sector, which limits the broader, economy-wide consumer benefit of any coal price reductions.

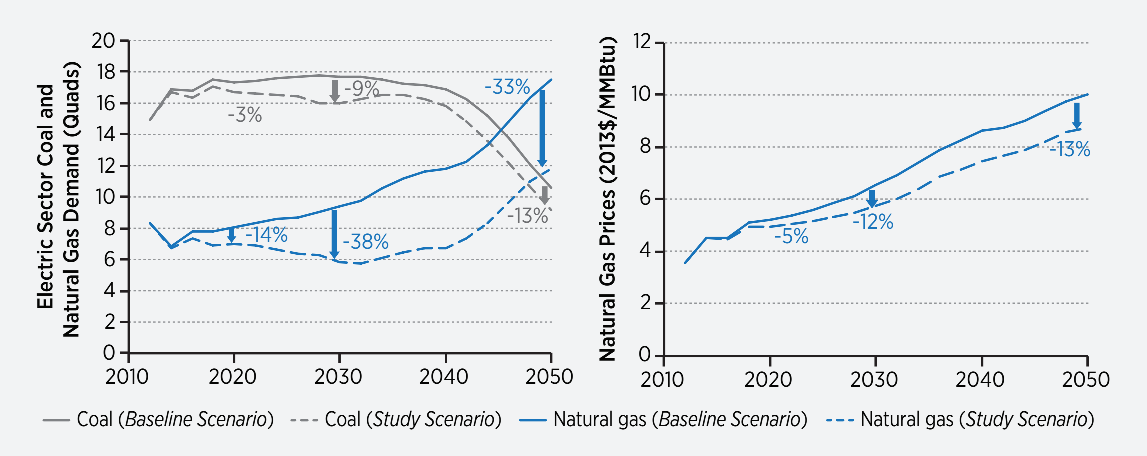


Figure 3-42. Reduction in demand for, and price of, fossil fuels under the *Study Scenario*

economy, and not able to fully account for such macro-economic impacts. This rebound effect, which might also include an increase in natural gas exports, would presumably lead to smaller market-wide price reductions than are shown in Figure 3-42. The impact on overall consumer savings is less clear, as the smaller price reductions would benefit a larger amount of consumption due to the rebound, leaving the aggregate dollar impact uncertain.

Notwithstanding these caveats, the $280 billion is equivalent to a levelized *consumer* benefit from wind energy of 2.3¢/kWh of wind.[133] Considering a household with a typical level of natural gas consumption, the estimated natural gas bill reduction benefit equates to an average of $0.40/month from 2013 to 2020 and $1.50/month from 2021 to 2030, increasing to $2.60/month from both 2031 to 2040 and 2041 to 2050.

Finally, some stakeholders point to the potential impact of increased wind power deployment on reducing wholesale electricity prices in organized competitive markets. Though not quantified here, the nature of this impact and relevant literature analyzing it are discussed in Text Box 3-6.

3.10.2 Wind and Natural Gas: Competitors and Partners in the Electric Sector

The significant displacement of gas-fired generation shown in Figure 3-25 under the *Study Scenario* (relative to the *Baseline*) suggests that utility-scale wind and gas compete in the electric sector. A closer analysis, however, reveals that gas-fired and wind generation are important partners in the *Study Scenario*, and that their combined presence may yield diversity-related benefits. In particular, despite being partially displaced by wind, natural gas continues to play a major role in the electricity sector under the *Study Scenario*, with demand eventually rising above today's levels (Figure 3-24). In addition, gas-fired *capacity* is not displaced as much as gas-fired generation under the *Study Scenario* (see Section 3.5.1), since a high-wind future requires a significant amount of flexible capacity to help integrate wind power, meet peak loads, and maintain system reliability. Ensuring that gas plants are adequately compensated for providing these services may be a precondition to achieving the *Study Scenario*.

133. This **levelized** impact is calculated by dividing the discounted benefit by the discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario.* When instead presented on a **discounted,** average basis (dividing the discounted benefit by the non-discounted difference in total wind generation in the *Study Scenario* relative to the *Baseline Scenario*), the value is 1.1¢/kWh of wind.

Text Box 3-6.

Impact of Wind Power on Wholesale Electricity Prices

One potential impact of wind energy not explicitly analyzed in the *Wind Vision* is its potential to lower wholesale electricity prices in the short run (i.e., within the time it takes new generation to be built or to retire). In particular, in organized, competitive wholesale markets such as those in many parts of the United States, the wholesale price is largely based on the variable cost of the most expensive generator required to meet demand. The addition of wind lowers demand for power from other generators, resulting in lower-cost generators setting wholesale prices. This short-run reduction in wholesale prices is often referred to as the "merit-order effect." This effect is not present, or is present to a lesser extent, in still-regulated markets that operate in a cost-plus environment (rather than an environment in which the marginal generator sets the price for all generation) and in markets where wholesale purchases are a subset of supply costs.

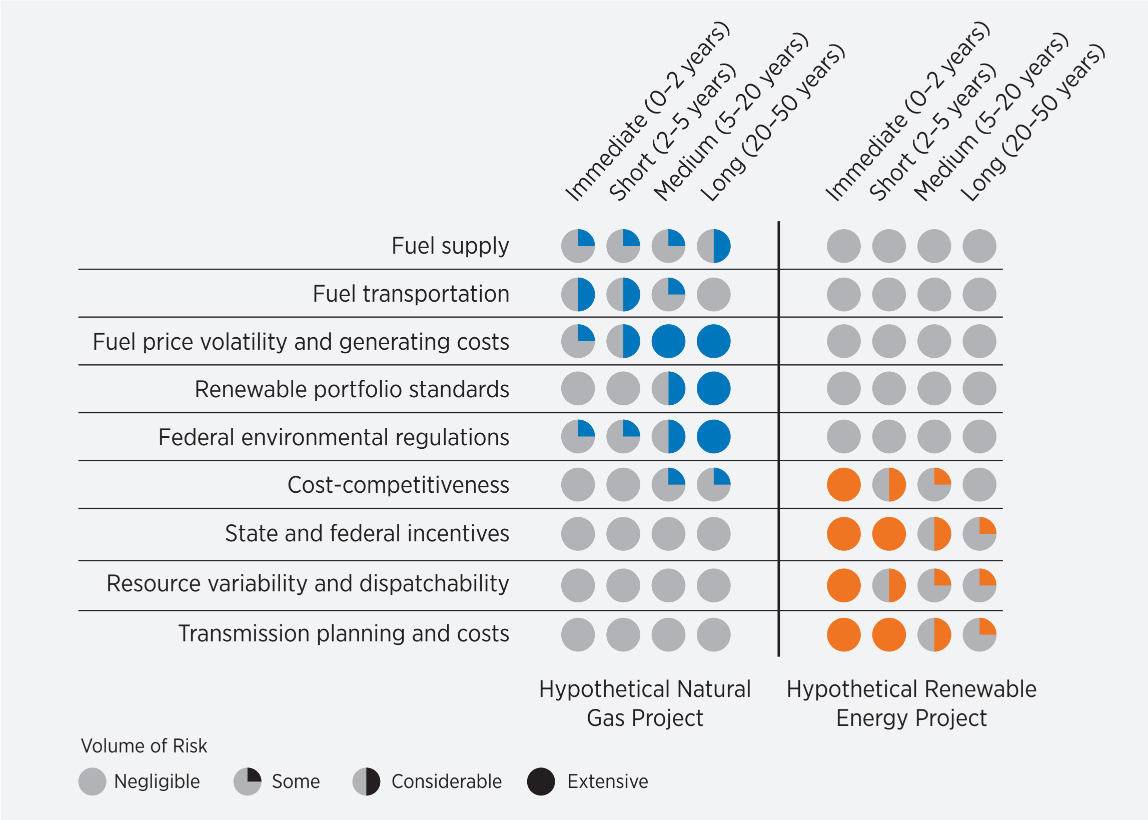
The magnitude of this effect has been estimated through simulations [66, 196, 197] and empirical analysis [198, 199]. In a review of many studies, Würzburg et al. [200] find a roughly 0.1¢/kWh (within a range of 0.003¢/kWh to 0.55¢/kWh) reduction in wholesale prices per percentage penetration of wind energy. The price effect is expected to be larger when plants with different fuels and efficiencies are used (i.e., when the generation supply curve is steep), whereas a smaller effect is expected if similar plant types are consistently on the margin [113]. Likewise, a relatively small effect of wind on wholesale prices was found in the hydro-dominated region of the Pacific Northwest [201]. Section 3.13.1.3 discusses this effect as it relates to offshore wind applications.

As with the impact of wind on natural gas prices (see Section 3.10.1), the change in wholesale electricity prices with the addition of wind affects electricity customers and generators differently. Assuming demand is inelastic (meaning demand does not increase substantially as the wholesale power price is reduced), customer costs are reduced by the difference in wholesale price times the amount of power purchased from the market. This reduction in costs for customers, however, is equal to the reduction in revenues earned by generators selling power in this market. Hence, just as with the impact of wind on natural gas prices, the merit-order effect results in a transfer of wealth from generators to consumers, and does not reflect a net increase of societal welfare [202].

There are two other reasons wholesale price effects are not separately quantified in the *Wind Vision* report. First, the modeling tool used here (ReEDS) estimates the total costs of producing electricity—it is not capable of estimating hourly wholesale market prices, and does not separately identify impacts to consumers versus impacts to generators. Second, as described below, the merit-order effect may be temporary. This is unlike the impact of wind on natural gas prices, which are presumed to have a long-term price response to altered demand conditions because the underlying gas resource is exhaustible.

The reason a persistent, long-term merit-order effect is less likely is that a reduction in revenue to generators reduces the incentive for new generators to enter a market or for existing generators to stay in a market [203, 204]. Sustained reductions in wholesale prices may therefore change the amount and type of generation capacity. In the long run, a number of studies suggest that, with high wind penetration, the generation mix will shift away from generators with higher up-front cost but lower variable costs (i.e., coal and perhaps combined cycle gas turbines) to generation with lower up-front cost but higher variable cost (i.e., natural gas plants, and perhaps especially combustion turbines) [170, 205, 206]. As a result of the increased investment in plants with higher variable costs, wholesale prices may not decrease in the long run to the same degree as observed in the short run.

Two characteristics of the impact of wind on wholesale prices that are expected to endure in the long run are an altered temporal pattern of short-term prices and an increase in short-term price volatility. Prices will be low during periods with high wind generation but can still be high in periods with low wind and high load [207]. The impact and importance of these altered prices—both due to short-term merit-order effects and long-term changes in price volatility—on electricity markets, resource adequacy, system flexibility, and revenue sufficiency are topics of current concern, as discussed briefly in Section 2.4.6.



Source: Lee et al. (2012) [208]

Figure 3-43. Qualitative framework for evaluating investment in new natural gas or wind projects by risk source, magnitude, and time scale

Utility-scale wind and gas-fired generation can complement each other in a number of ways within an overall electric system portfolio, given the diverse and often opposing characteristics and risks associated with these two resource types [208, 209]. For example, as suggested in Figure 3-43 and as described in Lee et al. [208], a portfolio that includes both wind and gas can help to partially protect consumers against natural gas price and delivery risk, while also providing insurance against the unknown costs of potential environmental regulations. Continuing to invest in and deploy a more diverse portfolio that includes renewable energy reduces the risks associated with locking in to a narrow range of technologies,[134] and may also enhance long-term energy security by preserving the nation's finite natural gas resource. At the same time, the inclusion of natural gas in this same diverse portfolio can mitigate the consumer price impact of any potential loss of federal tax incentives for wind, help manage wind output variability, and help minimize the need for and cost of new transmission.[135]

134. In addition, including offshore wind in the portfolio would help to prevent the possible premature lockout of a promising technology whose costs may decline significantly in the future as a result of deployment-related learning.

135. Gas-fired generators can often be sited closer to load than can wind generators, thereby minimizing the need for new transmission. In addition, pairing wind with flexible gas-fired capacity may allow for greater utilization of transmission assets than if used for wind generation alone.

3.11 Workforce and Economic Development Impacts

Workers are needed to develop, construct, operate, and maintain wind projects. In addition, supply chain workers manufacture and assemble turbine components, and businesses provide financial, legal, and other services. These workers, in turn, support additional jobs in their communities through purchases at restaurants, daycare centers, retail outlets, and more. Jobs create opportunities for local economic development, as do other local impacts associated with wind-related manufacturing and deployment, such as property taxes and land lease payments. An extensive body of literature has analyzed these impacts within the context of the U.S. wind sector [1, 210, 211, 212, 213, 214, 215].

The potential *national* wind sector labor force required to achieve the *Study Scenario* is analyzed here. Because these impacts are uncertain, depending in part on the future competitiveness of U.S. wind manufacturing, a range of potential labor force needs is quantified. Section 3.12.1 elaborates on these results, focusing on *local and state-specific* impacts. Section 3.13 provides additional context on the economic development aspects of offshore and distributed wind applications, respectively.

This section focuses on the potential "gross" wind-related labor force and economic development impacts of the *Study Scenario*[136]; it does not include an assessment of gross wind-related jobs in the *Baseline Scenario*, or of "net" economy-wide impacts. Increased wind generation will directly displace demand for natural gas, coal, and other sources of electric generation, impacting job totals and economic development associated with those sectors of the economy. Additionally, to the extent that increased wind deployment impacts the cost of energy, or has other macro-economic effects, this too may affect employment in the broader economy. Though not covered here, studies that have evaluated the economy-wide net effects of renewable energy deployment have shown differing results in terms of the net impact of renewable energy deployment [216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228].[137] In general, however, there is little reason to believe that net impacts are likely to be sizable in either the positive or negative direction (e.g., [227]). Brietschopf et al. [229] provide guidelines for the estimation of both the gross and net effects of renewable energy on employment, noting that input-output models can be useful for gross effects, but that a complete net-effects analysis requires the use of macroeconomic, economy-wide models.

3.11.1 Methods and Assumptions

To assess the potential gross wind-related employment and economic development impacts of the *Study Scenario*, this analysis uses the land-based and offshore wind Jobs and Economic Development Impacts (JEDI) models. JEDI is an input-output model designed to estimate the jobs, earnings, and gross output (economic activity) associated with energy projects. JEDI has been used extensively in both national and local assessments of land-based and offshore wind.[138] For more information about JEDI and its limitations, as well as further explanation of the metrics it reports, see Appendix I.

Three key sets of parameters are used to calculate labor needs in JEDI: deployed capacity, expenditures, and domestic content. Land-based and offshore wind power deployment in the United States and underlying expenditures come from the *Study Scenario*, described in Section 3.1.3. No export of U.S. wind-related goods and services is assumed. In reality, an export market for domestically manufactured wind equipment already exists—both for utility-scale wind [20, 232] and for distributed wind (primarily those 100 kW and under in size; see [233] and Chapter 2). The continuation or expansion of these existing exports would increase domestic wind-related jobs. Additionally, jobs associated with the increased interconnection and transmission infrastructure required under the *Study Scenario* are excluded, as are jobs

136. This section evaluates the impacts of the *Central Study Scenario* only. See Section 3.1.3 for detailed explanation of the scenarios. The ranges presented in this section are driven by the range of domestic content parameters evaluated, and not by the range of ReEDS scenario results.

137. Questions also remain as to whether any such effects serve as economic justification for government policy (e.g., [50, 117, 230, 231].

138. For examples of JEDI use in national studies, see, e.g., [1, 241, 242]. For examples of JEDI use in local studies, see, e.g., [213, 243, 244, 245, 246].

associated with behind-the-meter wind applications. Incorporation of these impacts would further increase the jobs estimates reported in this section.

Domestic content is defined as the portion of specific expenditures associated with wind deployment in the United States that is procured—and produced, in the case of manufactured goods—domestically. The extent to which wind developers, turbine manufacturers, and operators source components and services domestically depends on a number of factors (Figure 3-44; see also [20, 234, 235, 236, 237, 238, 239, 240]). Transportation costs and logistical complexity increase with larger, heavier components such as towers, blades, and offshore foundations, which tends to increase domestic sourcing.[139] International manufacturers, however, can often produce components at a lower cost than their U.S. counterparts. This is especially true for components that require significant amounts of labor and can be produced in countries with lower prevailing wages, or for components requiring materials that are less expensive in some countries, e.g., steel.

As discussed in Chapter 2, the domestic wind supply chain has strengthened since the early 2000s, albeit with some pullback since 2012. The steady, sustained deployment envisioned in the *Study Scenario*—a scenario that reduces the risk of fluctuations in demand for wind-related businesses—would, all else being equal, continue to strengthen the domestic manufacturing market. This trend would also be supported by the expected continued growth in turbine size, which will create greater transportation costs and complexities that can be mitigated through more localized manufacturing and assembly. Another development that may increase domestic content is increasing production automation and the associated decrease in labor needed to manufacture and assemble wind components, which will make the United States more globally competitive with countries that have comparatively lower labor costs. Additionally, manufacturers are developing new technologies such as hybrid towers[140] that could be manufactured completely or partially on-site, potentially further supporting domestic content. Finally, lower natural gas prices will reduce the materials cost for wind-related domestic supply (e.g., steel, plastics, and adhesives), which utilize natural gas in their manufacture.

There are, however, other trends that could lead to decreases, or limit increases, in domestic content (Figure 3-44). The most significant could be the

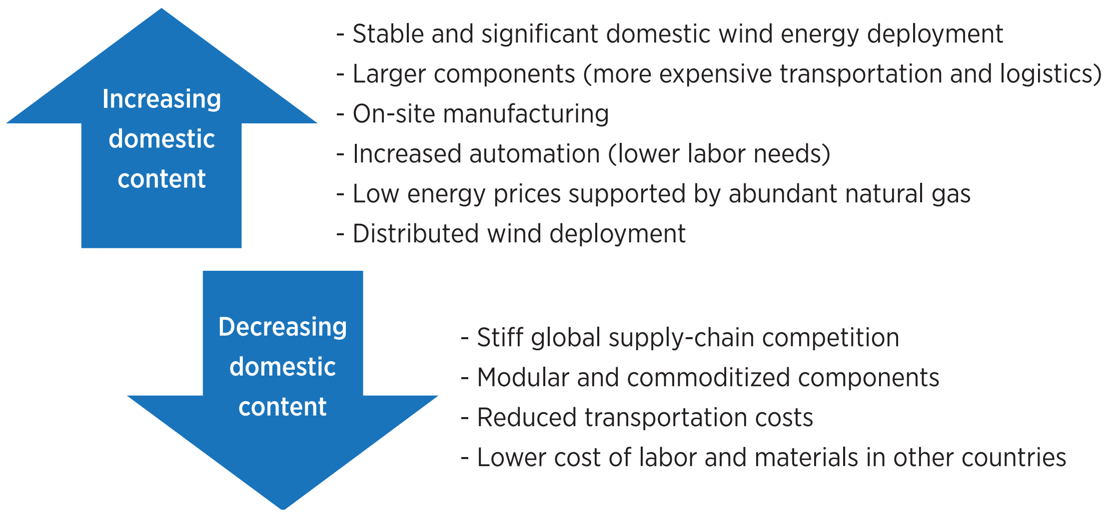


Figure 3-44. Factors that could increase or decrease domestic content of wind equipment installed in the United States

139. In the case of operational wind projects, operators may choose domestically produced components to minimize downtime created while waiting for replacement components to arrive from an international source or shipping components overseas for repair.

140 Hybrid towers are made out of steel along with concrete that is typically poured at the construction site.

development of modular, commoditized components—for example, blades and nacelle components. These technologies ease transportation constraints, thus making imports more cost competitive. Additionally, stiff competition among turbine manufacturers has led to supply chain consolidation, with manufacturers seeking only the lowest-cost components within their increasingly global supply chains. Assuming this trend continues, there may be an increasing concentration of component manufacturing and assembly in locations and facilities that offer the absolute lowest-cost delivered prices, with larger manufacturing facilities potentially offering economies of scale.

To account for uncertainty about these various trends, a range of component- and activity-specific domestic content assumptions are used for the *Study Scenario* workforce analysis (Appendix I). These ranges accommodate some potential shifts in global and industrial trends and allow for other unknowns, including changes in exchange rates, import tariffs, natural resource prices, and manufacturing and transportation technology. Under both the lower and higher ranges of domestic content, achieving the *Study Scenario* is assumed to support a robust domestic supply chain given the steady, significant growth in wind deployment envisioned. The lower case, however, assumes a greater tendency toward international supply, whereas the higher case presumes that the trends toward domestic supply predominate. Specifically, the lower case is intended to reflect, loosely, the level of domestic content achieved for 2012 installations in the United States (see, e.g., [20]). It is assumed that the wind deployment under the *Study Scenario* (which is both significant in magnitude and far more stable on a year-to-year basis than historical deployment levels) is likely to be sufficient to support that historical level of domestic manufacturing. Given the potential for even greater localization of manufacturing with the steady, significant growth in the *Study Scenario*, the higher case assumes much higher levels of domestic content.

Table 3-6. Domestic Content Assumptions for Land-Based and Offshore Wind

Component	Average Domestic Content (2013–2050)	
	Lower	Higher
Towers	60%	90%
Blades	60%	90%
Nacelle components	20%	50%
Balance of plant materials	80%	95%
Labor (construction and O&M)	100%	100%
Replacement parts	30%	60%

Note: Offshore substructure and foundation costs are placed in the "Towers" category, above. Replacement parts include all parts replaced during scheduled and unscheduled maintenance.

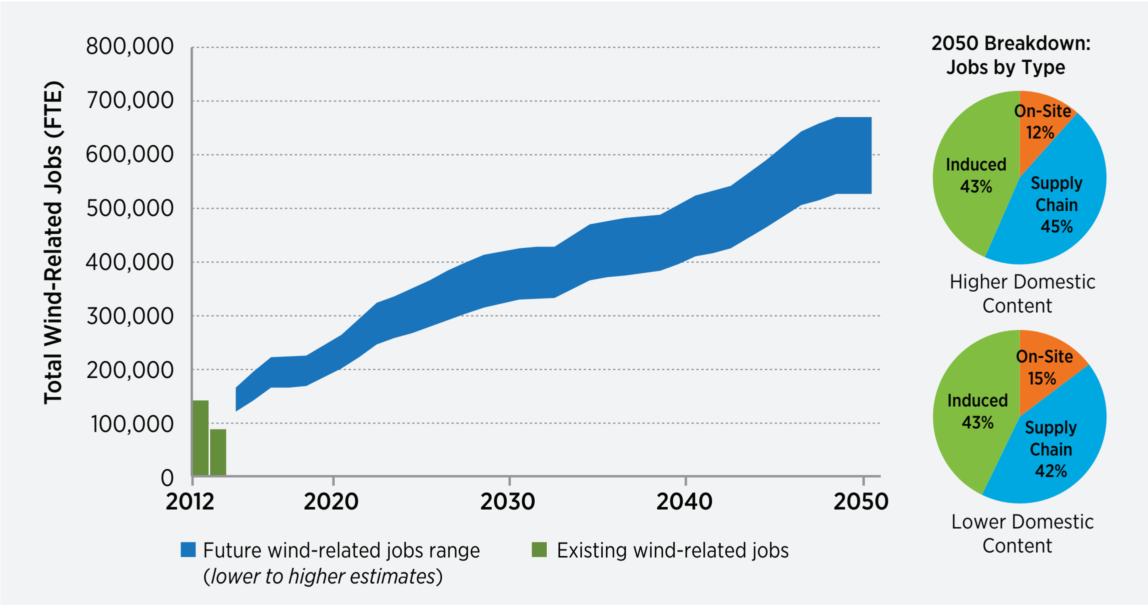
3.11.2 Gross Employment and Economic Development Impacts

Increasing wind deployment will support jobs directly or indirectly related to the U.S. wind industry in manufacturing, construction, and O&M. Figures 3-45 and 3-46 show the estimated total number of gross full-time equivalent (FTE) jobs[141] under the *Study Scenario* from 2020 to 2050, based on the range of domestic content assumptions.[142] These figures encompass jobs associated with both the construction and operation phases of wind project development, and include induced jobs. Three different types of jobs are identified (for more information, see Appendix I):

- **Onsite jobs** come directly from labor expenditures and include O&M technicians and construction workers, as well as labor associated with project development.
- **Turbine and supply chain jobs** relate to the supply of equipment, materials, and services to project operators and developers. These include manufacturing/production, as well as business-to-business services such as accounting, legal services, finance, and banking.
- **Induced jobs** are supported by on-site and supply chain workers who spend money in the United States. These include retail, food service, education, and entertainment jobs.

141. An FTE job is the equivalent of one person working full-time (40 hours per week) for one year or two people working half-time (20 hours per week) for one year.

142. Note that all jobs estimates presented here are reported as four-year rolling averages, rather than as yearly point estimates from JEDI, in order to reflect the planning and development times for land-based and offshore wind.



Note: Existing job estimates for 2012 and 2013 utilized American Wind Energy Association data for on-site and supply chain jobs and then the JEDI model to estimate the additional induced jobs.

Figure 3-45. Wind-related gross employment estimates, including on-site, supply chain, and induced jobs: 2012–2050

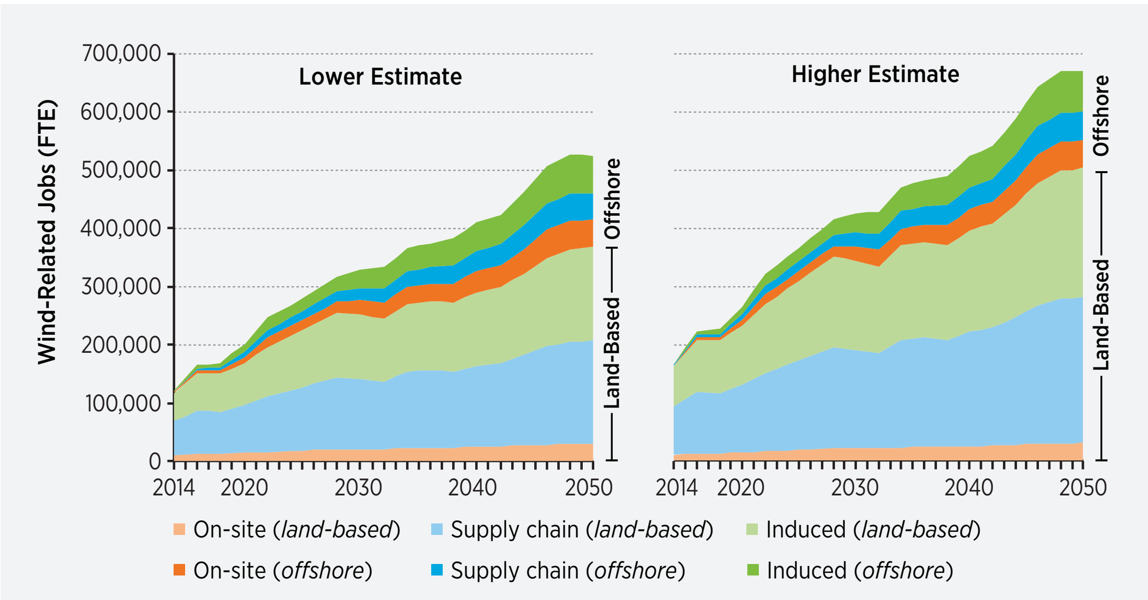


Figure 3-46. Wind-related employment estimates for land-based and offshore wind

Table 3-7. Construction-Phase Estimated FTE Jobs

Type of Job	2020	2030	2050	2020	2030	2050
	Low Estimate (FTE)			High Estimate (FTE)		
On-site and project development	17,000	32,000	58,000	17,000	32,000	58,000
Turbine and supply chain	58,000	85,000	139,000	81,000	118,000	189,000
Induced	48,000	75,000	127,000	65,000	100,000	165,000
Total	**123,000**	**193,000**	**323,000**	**163,000**	**250,000**	**412,000**

Note: Totals may not sum because of rounding. Induced jobs are supported by on-site and supply chain workers who spend money in the United States on retail, food service, education, and entertainment.

Table 3-8. Operation-phase Estimated FTE Jobs

Type of Job	2020	2030	2050	2020	2030	2050
	Low Estimate (FTE)			High Estimate (FTE)		
On-site labor	7,000	12,000	19,000	7,000	12,000	19,000
Local revenue and supply chain	32,000	57,000	85,000	44,000	76,000	112,000
Induced	39,000	67,000	98,000	51,000	88,000	127,000
Total	**78,000**	**136,000**	**202,000**	**102,000**	**176,000**	**258,000**

Note: Totals may not sum because of rounding. Induced jobs are supported by on-site and supply chain workers who spend money in the United States on retail, food service, education, and entertainment.

As shown in Figure 3-45, total estimated wind-related (including induced) jobs range from 201,000 to 265,000 in 2020; 329,000 to 426,000 in 2030; and 526,000 to 670,000 in 2050. In 2050, 12–15% of these jobs are projected to be on-site, 42–45% are turbine and supply chain jobs, and 43% are induced. These totals compare to the American Wind Energy Association's estimates of 80,700 wind-related on-site and supply chain jobs in the United States at the end of 2012, and 50,500 jobs at the end of 2013 [15], which corresponds to approximately 140,000 and 90,000 jobs when also considering induced impacts.

Figure 3-46 provides additional detail, by general job type and by land-based and offshore wind. As shown, the proportion of offshore-related jobs increased with time: by 2050, 23–28% of the total wind-related jobs are driven by offshore wind development. A further regional segmentation of the on-site jobs is provided in Section 3.12.

Under the lower domestic content scenario, total *construction-phase* impacts are estimated to be 123,000 FTE jobs in 2020; 193,000 in 2030; and 323,000 in 2050 (Table 3-7). Under the higher domestic content scenario, there are 163,000 jobs in 2020; 250,000 in 2030; and 412,000 in 2050. The majority of these positions are turbine and supply chain jobs—approximately 46% under the higher scenario and 43% under the lower scenario.

Total *operation-phase* jobs are estimated to be 78,000 in 2020; 136,000 in 2030; and 202,000 in 2050 under the lower scenario (Table 3-8). Under the higher scenario, there are 102,000 jobs in 2020; 176,000 in 2030; and 258,000 in 2050.

In addition to employment implications, wind project development can also impact local communities through, for example, land lease payments and local property taxes. Under the *Study Scenario*, wind power capacity additions are estimated to lead to land-based lease payments that increase from $350 million in 2020 to $650 million in 2030, and then to $1,020 million in 2050. Offshore wind lease payments increase from $15 million in 2020 to $110 million in 2030, and then to $440 million in 2050. Property tax payments associated with wind projects are estimated at $900 million in 2020; $1,770 million in 2030; and $3,200 million in 2050.[143]

3.11.3 Occupational Needs

These results provide estimates of the future workforce associated with the *Study Scenario*, but do not characterize who might fill these positions or what skills they may need. Workers who fill positions supported by the *Study Scenario* may be previously unemployed, may move from other industries, or may come from educational or vocational training programs. Many of the workers needed under the *Study Scenario*, at least in the near future, may already be employed in the wind industry.

Notwithstanding the potential availability of some already qualified workers, additional training and educational programs are likely to be necessary. In particular, according to a 2013 report, the United States may need to offer increased wind-related education and training in several areas in order to reach 20% wind penetration by 2030 [247]. This includes post-secondary professional certificate programs (90 additional programs needed), bachelor's degree programs (30 additional programs needed), and master's, Ph.D., and law degree programs (10 additional programs needed).

3.12 Local Impacts

It is important to examine the potential positive and negative local impacts of wind development. Local impacts covered in this section include: economic development, land and offshore use, wildlife, aviation and radar, aesthetics and public acceptance, and health and safety. Where it is feasible, potential impacts are quantitatively analyzed. For some impacts, quantification is feasible given the existing literature base; for example, the impact of wind on scenic views. Where quantification of the impacts is not possible, impacts are discussed based on an understanding of current wind energy technology, developments since 2003, and consideration for what might occur during the timeframe of the *Wind Vision* study (2014–2050).

The *Study Scenario* calls for large-scale wind deployment that will have numerous and wide-ranging impacts. The *Wind Vision* analysis concludes that, with responsible wind turbine siting, improvements in technology, and a better understanding of potential impacts and mitigation options, it is possible to achieve this scenario. This is in part because of the enormous wind resource base in the United States. Even if large portions of the country with wind potential do not see expanded wind deployment due to different energy choices or local decisions, other wind-rich areas should be able to provide enough wind energy to reach the wind penetration levels of the *Study Scenario*. Expanded impact mitigation and reliance on lower wind resource areas may also help reduce or avoid areas with possible greater negative local impacts. At the same time, such strategies can increase the cost of wind energy. Careful consideration is therefore warranted when balancing positive and negative impacts, mitigation measures, and project economics.

143. These land lease and property tax figures are solely associated with wind capacity additions and do not include related payments that result from wind equipment manufacturing and supply chain investments. This analysis uses JEDI default property tax and land lease figures. Nationally, default annual property tax payments are $7,399/MW. Annual lease payments for land-based wind are $3,000/MW; see Appendix I for more information about the calculation of offshore wind lease payments. All dollar figures are in 2013$.

3.12.1 Local Economic Development Impacts[144]

Local economic development benefits of wind energy can include jobs and additional financial benefits. The gross national economic development, employment, and workforce implications of the *Study Scenario* are described in Section 3.11. These **national** results, however, mask the **local** economic and employment impacts of wind energy.[145]

Although every wind power project is different, a representative 100-MW operational wind project, whether land-based or offshore, is likely to employ 4–6 people on-site for the life of the facility. Land-based plants of this size support an additional 30–80 on-going jobs nationally, through supply chain and subcontracted activities, and as a result of on-site and supply chain worker expenditures (the latter are often called "induced" jobs). Offshore wind projects of a similar size are likely to support a somewhat larger number of these jobs, about 30–110.[146]

Focusing only on on-site construction and operations jobs, Figure 3-47 provides estimated state-by-state gross wind employment numbers in 2050, using the same tools as in Section 3.11.1. Estimated state-level on-site wind jobs are, not surprisingly, directly linked to the geography of the land-based and offshore wind deployment under the *Study Scenario*. Domestic supply chain (e.g., manufacturing) and induced jobs, though analyzed nationally in Section 3.11, are not shown in these figures since the location of these potential future jobs could not be accurately assessed.

In addition to jobs, there are other economic benefits to local communities that host wind projects, such as payments to landowners for land leases and property tax revenue to counties and states. Estimates of total land lease payments and property taxes under the *Study Scenario* are summarized in Section 3.11.2 on a national basis, but these, too, have a local context. Although annual land lease payments vary by project, a typical payment might be \$3,000/MW. Property taxes also vary by location, but average annual payments of more than \$7,000/MW are common.

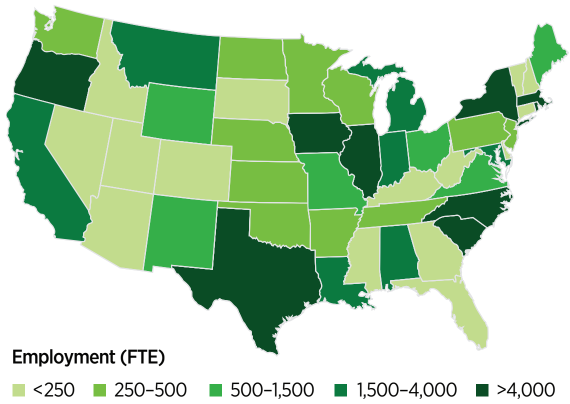


Figure 3-47. Estimated on-site wind project employment, 2050

Wind projects on public lands or in public waters would also provide lease payments to the state and other relevant jurisdictions in close proximity to the installations.[147]

Finally, research shows that the gross economic development impacts from community and distributed wind projects are somewhat more likely to remain in the community within which those projects are located. This is because community and distributed wind feature local ownership. For example, Lantz and Tegen [248] find that community wind projects have construction-phase employment impacts that are 1.1–1.3 times higher than typical utility or investor-owned projects, while operation-phase impacts are 1.1–2.8 times higher. See Section 3.13 for a further discussion of the unique economic development attributes of distributed and offshore wind.

3.12.2 Land and Offshore Use

All electricity generation sources require land—not only for the physical power plant, but also for supply chain activities, fuel extraction, and fuel delivery. The magnitude and nature of these land uses are diverse, making comparisons among different energy sources challenging. Given those challenges, the

144. The analysis and results presented in this section, as in Section 3.11, relies on the NREL JEDI model. For more details, see Appendix I. Also note that the analysis presented here is based on the *Study Scenario* under *Central* assumptions only.

145. As in Section 3.11, the present section does not address "net" impacts, but instead focuses on the local impacts associated with wind power development alone.

146. *http://www.nrel.gov/analysis/jedi/*

147. *http://www.nrel.gov/analysis/jedi/*

present analysis focuses solely on the "gross" land and offshore use that might be required by wind power plants in the *Study Scenario*. The analysis does not evaluate the land savings associated with power plants and fuel usage displaced by wind production. Though the reduced burdens on land use associated with that displacement are not considered here, they can be significant. For example, Fthenakis and Kim [249] estimated the life-cycle land disturbance of wind and solar energy to be lower than the impacts of coal-generated electricity.

The amount of space that a wind power plant requires varies depending on a variety of siting requirements; however, a general value of 0.33 kilometers(km)^2/MW (82.4 acres/MW) constitutes a viable estimate for the facility boundary for both land-based and offshore wind development (see Chapter 2 for details). Within this facility boundary, however, only a relatively small amount of land is actually physically transformed or occupied permanently by turbines and related infrastructure. Analysis using satellite images of operating wind power plants completed by the U.S. Geological Survey, for example, indicates that land impacts for wind turbines as well as additional land use such as tree thinning, roads, and electrical infrastructure varies between 0.0011–0.043 km^2/MW (0.27–10.63 acres/MW) [250], with a mean of .0093 km^2/MW (2.30 acres/MW). The present analysis assumes a mid-point for land transformation of 0.01 km^2/MW (2.47 acre/MW), or approximately 3% of the project boundary area.[148] The remaining land within the overall project boundary can be used for other activities, such as farming and ranching, or left in its natural state.

For offshore wind projects, a range of values have been proposed for the boundary of projects along the Eastern Seaboard, between 0.20–0.60 km^2/MW (50.4–148.8 acres/MW) [251, 252, 253, 254]. For offshore plants, the physically transformed area is much less than for land-based facilities, though actual values for U.S.-based facilities will depend on pending legal and marine public safety issues for offshore wind development in public waters.

Focusing first on the area impacted by the turbine footprint, roads, and associated infrastructure and assuming a land use value of 0.01 km^2/MW, the *Study Scenario*[149] is estimated to require approximately 2,000 km^2 (500,000 acres) by 2030, and 3,200 km^2 (790,000 acres) by 2050. This transformed land is dispersed over a larger area that represents the combined boundary of the projects. Assuming a land use value of 0.33 km^2/MW, this larger area represents 67,000 km^2 (17 million acres) of land by 2030 and 106,000 km^2 (26 million acres) by 2050. Most of this larger area could also be used for other purposes, such as farming or ranching [255], though an even larger area would be impacted visually. Assuming the same boundary usage assumption as for land-based, the offshore wind deployment in the *Study Scenario* covers approximately 7,300 km^2 (1.8 million acres) of offshore area by 2030 and 29,000 km^2 (7.1 million acres) by 2050, only a small fraction of which would be physically transformed.[150] Although only indirectly tied to land use, it should be noted that the wakes produced by wind turbines can persist for several kilometers downwind of the actual wind plant. Impacts to land and other environmental characteristics resulting from downstream wakes are likely negligible, but have not been quantified.

To put these land and offshore areas in context, the total land area affected by wind power installations in the *Study Scenario* is less than 1.5% of the land area of the contiguous United States, with the vast majority (97%) of that land area remaining available for multiple purposes. For comparison, the areas of West Virginia and Kentucky are 63,000 km^2 and 105,000 km^2, respectively, similar to the expected facility boundary for all land-based wind deployments in 2030 and 2050. The area of the nation's golf courses, approximately 10,000 km^2, is three times the estimated transformed land area from wind development by 2050 [256], where "transformation" includes the amount of land impacted by turbine footprints, roads, and associated infrastructure.

Figures 3-48 and 3-49 show the relative size of expected land and offshore areas containing and transformed by wind facilities in the *Study Scenario* for 2030 and 2050, respectively, by state.

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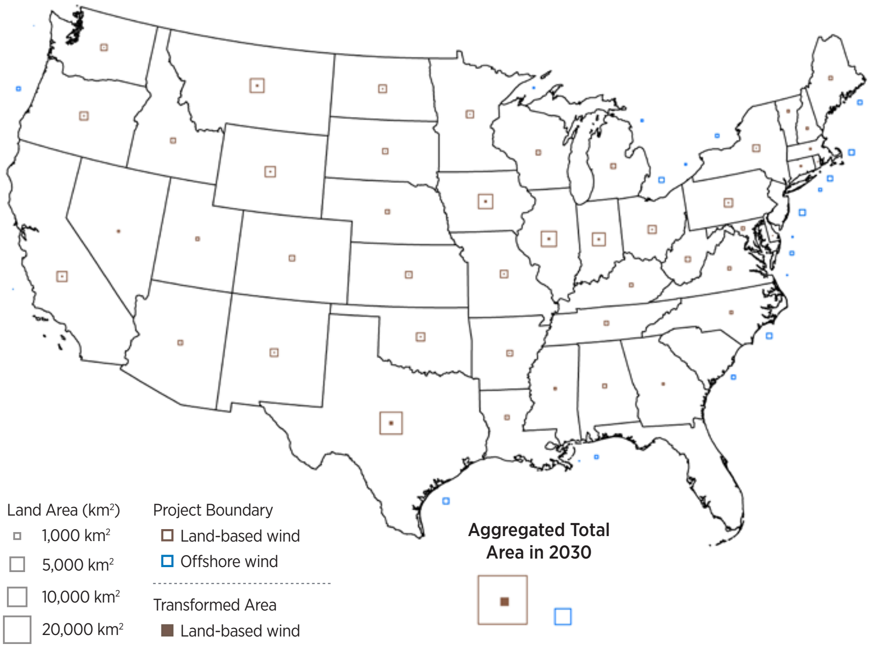
148. Denholm et al. [255] find direct land use to equal, on average, just 1% of the project boundary, using a somewhat different definition for land use than that used here.

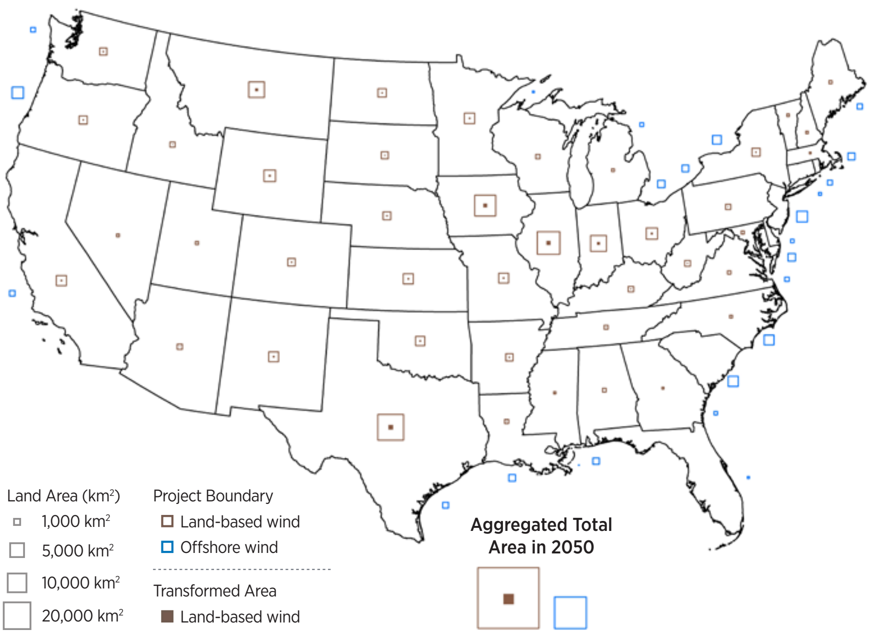
149. The analysis presented in this section is based on the *Study Scenario* under *Central* assumptions only.

150. Given the uncertainties around offshore development due to unresolved legal and marine public safety issues, only the facility boundary offshore area is estimated for the *Study Scenario* and not the transformed area.



Note: Map illustrates expected land and offshore area requirements in 2030 for the *Study Scenario*, by state. Transformed land area is the wind plant area directly impacted by turbines, roads, and other infrastructure. The project boundary area includes spacing between turbines that can be used for other purposes such as ranching and farming.

Figure 3-48. Land-based and offshore area requirements for *Study Scenario,* 2030



Note: Map illustrates expected land and offshore area requirements in 2050 for the *Study Scenario*, by state. Transformed land area is the wind plant area directly impacted by turbines, roads, and other infrastructure. The project boundary area includes spacing between turbines that can be used for other purposes such as ranching and farming.

Figure 3-49. Land-based and offshore area requirements for *Study Scenario,* 2050

3.12.3 Wildlife Impacts

Climate change is considered a significant threat to wildlife, and rapidly replacing fossil fuel-based energy technologies (e.g., coal and gas) with low-carbon options (e.g., wind) has been identified as a crucial step in limiting the impacts of climate change. Like all energy sources, however, electricity generation from wind has impacts on wildlife that must be considered. Although there is no regulated national process regarding pre-construction environmental assessments and the literature remains unclear on how these assessments affect outcomes, concerns about wildlife impacts are reflected in wildlife surveys and assessments typically completed in the siting and permitting of wind projects [257]. With the increased levels of deployment described by the *Study Scenario*, a greater impact on wildlife from wind will be expected. However, impacts can be reduced on a per-turbine basis using improvements in project siting, impact minimization, mitigation, and compensation strategies. Impacts should also be balanced against the wildlife benefits that wind energy might provide through the displacement of other generation options, their direct impacts to wildlife, and their impacts on climate change.

An overview of the current impacts of wind development on avian and bat species is provided in Chapter 2. Increasing wind deployment under the *Study Scenario* through 2050 is not expected to directly and materially impact most common bird species, i.e., passerines. Direct fatalities of as many as 1 million birds per year could be expected in 2030 and 2 million per year in 2050,[151] using current fatality estimates and not taking into consideration additional improvements in siting practices and future avoidance and minimization techniques that could reduce impacts over time. Although general and regionally-specific cumulative impacts must be considered, the direct wildlife impact associated with wind energy development and operation represented by these figures is a small fraction of the birds killed annually by communication towers, power lines, and buildings (See Table 2-7).

Though learning is still needed regarding impacts of wind deployment on common bat species, the overall impact is expected to be low, especially with the development of effective avoidance, minimization, and mitigation strategies over the last few years, as outlined in Section 2.8.1. The general and regional cumulative impacts of White Nose Syndrome as well as anthropogenic causes, however, may be significant, especially for populations that are already imperiled. The impacts of the *Study Scenario* on rare, protected, and endangered species must also be considered. In some instances, future wind project siting might simply avoid areas in which such species live. In other cases, active minimization or compensation strategies can be employed, such as changing operational conditions of wind turbines during periods of high risk associated with bat migration, or supporting species recovery programs to minimize the net species impact, if appropriate. Such strategies will increase the cost of wind energy, and those costs would ideally be balanced against the benefits of wind energy in facilitating a transition away from conventional energy sources and related climate and wildlife impacts [258].

Although the relationship between pre-construction activity and post-construction impacts, particularly for bird and bat collisions, is not well understood [257], the wind industry has and is expected to continue to invest in assessing risks to wildlife, and in avoiding, minimizing, or compensating for predicted project-level impacts. The wind community also continues to help fund larger-scale research to reduce the impact of expanded wind development. For example, the industry co-founded the American Wind Wildlife Institute in 2008 to facilitate research aimed at minimizing impacts to wildlife. Given these efforts, a continuing reduction in the uncertainty around risk assessments is anticipated. This should increase consistency in the protocols for pre-construction wildlife surveys and post-construction monitoring, potentially leading to reductions in per-MW wildlife impacts and a more transparent process for understanding overall impact of expanded wind development. There are also efforts underway to make wildlife data collected

151. Collision fatality rates for birds at land-based facilities average 3–5 birds per year [257, 259, 260, 261]. Estimated annual fatalities in 2030 and 2050 use a conservative high average of 5 birds/MW per year and the *Central Study Scenario* estimate of 224 GW in 2030 and 404 GW in 2050. Specific mortality rates are dependent on the local habitat, and this simple calculation assumes a similar geographic distribution of further wind installations. Additionally, research indicates that avian impacts of offshore wind development will be reduced compared to land-based deployment. This offshore effect is not considered [262], likely leading to an overestimation of the potential impact. Finally, these estimates presume no further improvements in reducing fatality rates over time, which is a conservative conclusion.

at wind power plants available for scientific analysis, with the expectation that analyses of comprehensive datasets will reduce uncertainties about wildlife impacts and improve the ability to predict impacts during the siting process.

The broader, habitat-level impacts of wind energy on wildlife are less understood and are dependent upon numerous site-specific factors. Concerns often focus on indirect effects. For example, the disturbance from operating wind projects is hypothesized to cause species displacement, fragmentation of habitat, and demographic decline. Species of prairie grouse (in particular, greater sage-grouse and both greater and lesser prairie chicken) avoid breeding sites in the proximity of tall structures. Few published studies have tested this hypothesis regarding wind power plants [263, 264], and other studies [265, 266] have called into question whether tall structures themselves or other factors like road noise are the true cause of this effect. Even less is known about the wildlife impacts of offshore wind development in the United States. Existing studies and those anticipated to be done once the U.S. offshore wind industry develops can be expected to bolster data from Europe to facilitate assessing and, to the extent possible, mitigating any identified impacts. Baseline assessments and the mapping of use patterns and habitats of marine organisms that are likely to be impacted by offshore wind energy development are important as well, to allow wind developers to anticipate and mitigate potential impacts.

Though not all impacts can be fully mitigated, the process of siting wind power plants has evolved significantly since the early days of the industry and is expected to continue to do so over the coming decades, decreasing impacts on local wildlife. Further progress can be made with increased research on and information-sharing of the observed impacts of wind energy deployment, particularly in comparison to other energy-generating technologies. This will provide a better understanding of the tradeoffs between development of wind and other energy technology options.

3.12.4 Aviation Safety and Radar Impacts

Wind projects can impact aircraft and weather radar systems and general aviation. Assuming continued minimization of potential impacts and mitigation of any resulting impacts, the wind deployment levels under the *Study Scenario* are not anticipated to have a significant effect on critical missions served by advanced radars, e.g., flight safety, severe weather warnings, commerce, and control of U.S. borders and airspace. The total cost of wind projects may increase, however, to address these local issues through the implementation of increased mitigation measures, reduced site availability, and increased permitting requirements.

Future strategies to minimize and mitigate the effects of wind development on radar systems will likely include improved algorithms such as clutter filters and other filtering techniques, advanced signal processing, and intelligent detection algorithms. Further mitigation may occur through new technologies or variations of old technologies via hardware and software changes, such as the upgrade of Air Route Surveillance Radars, concurrent beam processing, creation of radar networks and fusing of data from multiple radars, or operational data-sharing. Other mitigation techniques that have been or could be used include project developer-supported adaptation (through personnel training) or, in rare instances, radar upgrades, repositioning, or mission relocation. Modeling, simulation, and smarter planning through improved siting tools will be important to remove and mitigate wind turbine and radar interactions. The U.S. Department of Defense has begun negotiating wind project curtailments with developers. These curtailments allow projects to proceed while insuring that the turbines will not impact defense operations during critical times. All of these advancements, combined with a growing understanding of issues and the deployment of new radar systems that are better at eliminating erroneous signals caused by wind turbines, will continue to mitigate the impacts of wind deployment.

Issues related to aircraft safety (beyond possible radar interference) may also be of concern. Although wind turbines may increase to more than 500 feet (152.4 m) in total height, federal permitting and requirements around critical infrastructure are not anticipated to impact overall deployment. Local aviation-related issues will also be addressed through increased mitigation measures such as the use of expanded lighting or flight avoidance technology and through increased permitting requirements. These steps could add modestly to the costs of wind development.

3.12.5 Aesthetics and Public Acceptance

Local community concerns about wind projects can be expected as wind development expands and approaches the levels of the *Study Scenario*. Future wind plants will likely be in closer proximity to larger population centers. A comparison of existing wind deployment by state against the expected deployment under the *Study Scenario* shows that a substantial amount of new wind will be located in states that have already experienced extensive wind deployment. Even in these states, though, significant additional wind deployment would be needed, often in areas without prior wind development. Additionally, many states and offshore areas that have not experienced significant wind development are anticipated to see new wind deployment under the *Study Scenario,* e.g., the southern Atlantic states, such as South Carolina, as well as southern states including Arkansas, Tennessee, and Alabama. Though wind development in remote areas is also anticipated, wind deployment levels under the *Study Scenario* could lead to increased local conflicts over aesthetic and other concerns, given greater development near population centers.

Public attitudes toward land-based and offshore wind are generally supportive [267]. Although not conclusive, research as recent as 2014 suggests that existing wind projects have not led to any widespread reduction in the home values of surrounding properties [268, 269, 270, 271]. Moreover, as previously described, the local positive economic development benefits of wind projects can be substantial, providing not only local jobs, but additional tax revenue and land use payments [210, 213, 245, 248, 272].

Despite these findings, public acceptance in communities that host wind facilities is highly dependent on local conditions and can change depending on whether benefits are provided and whether community members feel that their values are respected during the development process [273, 274]. Community conflicts surrounding potential wind development can and do occur. As a result, early community involvement, careful attention to local concerns, and advancements in development and siting procedures may be needed to achieve the wind deployment levels in the *Study Scenario* while also reducing the prevalence of local conflicts. Expanded community engagement using more accessible peer-reviewed information, increasingly sophisticated assessment tools, and technology advancements to mitigate potential impacts can help reduce local concerns. Ultimately, although doing so would increase the costs of wind deployment, the available U.S. wind resource is more than sufficient to meet the deployment needs outlined in the *Study Scenario* even if areas are removed from consideration or require expanded mitigation.

3.12.6 Potential Health and Safety Impacts

As with other electric generation facilities, there are several health and safety concerns that have been identified in the development and operation of land-based and offshore wind projects, including wind turbine blade-induced shadow flicker, sound, general safety, and marine safety. As described in greater depth in Chapter 2, much is already known and many studies have documented the limited potential impacts of wind development [274, 275, 276, 277, 278, 279]. Most of these issues are addressed through the implementation of thoughtful permitting and zoning guidelines and careful study during the project development process. As has been discussed previously, there are no defined standard guidelines for the permitting of wind power plants, although several examples have been publicly offered [280, 281, 282].

Although some questions remain, numerous state and federal organizations, non-governmental organizations, and the larger wind industry continue to work to understand, document, and mitigate current or future impacts. Over the long-term horizon of the *Wind Vision*, the number of turbines will increase dramatically, potentially increasing health and safety concerns and requiring careful attention. At the same time, with regulatory and statutory oversight, careful and considerate wind development, and use of mitigation strategies, health and safety impacts can be reduced.

This chapter has identified a large number of benefits to wind deployment for the nation as a whole: cleaner air, reduced water stress, stable energy prices and, in the longer term, reduced impacts from climate change. These larger national benefits must also be included in the consideration of the positive and negative local impacts of wind development. Ongoing communication of these benefits at the national and local levels will be essential to maintaining high levels of both general and local support for wind development.

3.13 Unique Benefits of Offshore and Distributed Wind

Offshore and distributed wind have unique benefits that should be considered in evaluating the overall value of wind power to the nation's electricity supply.

3.13.1 Offshore Wind

In order for offshore wind to be economically competitive, the cost of the technology needs to be reduced. Through innovation and increasing scale, however, this market segment could bring notable potential benefits. The attributes for offshore wind's contribution to the *Study Scenario* are characterized by a robust industrial base that evolves from the nascent state of 2013 to supply more than 80 GW of capacity by 2050. This deployment represents about 5.5% of the available offshore resource after exclusions for environmental and other protected areas or just 2% of the gross resource potential, estimated at 4,000 GW for offshore areas adjacent to the 28 coastal states [283]. Under the *Study Scenario*, the offshore wind industry would complement and bolster a strong land-based industry through the use of common supply chain components and the development of workforce synergies. While a sharp decline in offshore wind costs is anticipated with increased industrial scale (see Section 3.2.1), the following sections highlight unique cost drivers and benefits of offshore wind not otherwise assessed in Chapter 3 that may contribute to economic viability.

Major Renewable Resource for Coastal States

U.S. counties situated on the coasts constitute less than 10% of the country's total land area (excluding Alaska), but almost 40% of the total population [284]. With high land values and an average population density six times greater than in corresponding inland counties, coastal areas frequently lack suitable sites for new utility-scale electric generation facilities. From the perspective of land use and site availability in densely populated coastal states, offshore wind is one of the most potentially viable large-scale renewable energy options. In some cases, offshore wind may be one of the only electric generation options that can be practically developed at a large scale using indigenous energy sources.

Reduced Transmission Requirements

Building electric transmission lines from interior land-based wind (or other electric generation) sites to coastal population centers may avoid the need for new local, large-scale generation in these areas. There is, however, significant uncertainty associated with the cost of building new transmission, and even greater uncertainty associated with the feasibility of planning, permitting, and cost recovery [285]. For example, there is no currently accepted method of planning and allocating the cost of multi-state electric transmission projects spanning from the Midwest to the East Coast; in fact, there is evidence that some policy makers in coastal states are opposed to such infrastructure [286]. The development of offshore wind can reduce the need for new investments in long-distance transmission and avoid complex (and sometimes contentious) transmission projects [2, 64, 63]. At the same time, offshore wind does require some offshore transmission infrastructure, and so presents a unique opportunity for efficient centralized management of offshore transmission planning and development. Since the federal government and state governments control most of the offshore space, a new offshore transmission infrastructure could avoid some of the complexity and fragmentation resulting from numerous over-land private property easements and could provide a more robust electric network for congested coastal areas. This would be possible with or without offshore wind development.

Lowered Wholesale Electricity Prices

Offshore wind might have a more significant impact in lowering wholesale electric prices in coastal states, at least in the near term, than land-based wind in other regions. In a large portion of the eastern United States, as well as in California and Texas, electric markets feature locational marginal pricing. This leads to wholesale prices that vary along time and geography, and that incorporate three cost components: energy, transmission congestion, and transmission losses. The marginal cost of energy in these markets is set by the highest-priced available unit of electricity required to support load at any given point in time and space (see discussion of merit-order effect in Text Box 3-6). Higher prices are typically experienced during the day and during the summer, when load is high. Pricing is also higher in urban areas; for example, during the day in New York State, prices can average 50–100% higher in New York City and Long Island than in rural upstate areas.

Offshore wind can help lower transmission congestion and losses by taking advantage of relatively short interconnection distances to urban electric grids in coastal and Great Lakes states. This means that offshore wind could help depress locational marginal pricing in these areas, reducing electricity prices to utilities, at least in the short run. Though there are many nuances behind these possible effects (Text Box 3-6), and similar locational marginal pricing effects can apply to any generating source, the impact is potentially stronger for offshore wind due to its proximity to the highest transmission congestion regions, such as the northeastern United States. Research that has explored these effects includes that of Levitan and Associates [287] for New Jersey, Charles River Associates [288] for New England, and GE Energy, EnerNex, and AWS Truepower [63] for New England. Although these more global market price reductions cannot be attributed to lowering the cost of energy for offshore wind projects, they can potentially provide incentives at the utility level to raise the price point for grid parity with other energy sources.

Higher Capacity Value Relative to Land-Based Wind

The capacity value of a power plant is the amount of generation that can be relied upon to meet load during critical periods. The variability of wind energy has contributed to a general perception that it has a low capacity value. Indeed, some land-based wind energy projects have shown a poor correlation with peak demand, and the ReEDS modeling for the *Study Scenario* shows a steep decline in the capacity value of wind as penetrations increase toward 2050 (see Section 3.6.1). Notwithstanding these concerns, studies show that offshore wind in the mid-Atlantic, South Atlantic and New England regions has a higher capacity value than typical land-based wind sites. This is partly because the geophysical weather patterns responsible for peak electric loads on the East Coast often also enhance wind flows over adjacent offshore waters; offshore winds often peak in the afternoon and evening, whereas land-based winds often peak at night [63, 64, 289, 290]. As a result, the market value of offshore wind may be higher than that of land-based wind in the same region.

Fuel Diversity and Risk Reduction

As discussed in Section 3.10, the *Study Scenario* offers potential energy diversity and risk reduction benefits. Offshore wind, in particular, can help diversify coastal states' fuel mix and help them hedge against future price increases or supply disruptions of natural gas. Coastal states have among the highest electricity prices in the nation [4], driven in part by constraints in gas pipeline infrastructure coupled with congestion in the electric transmission system. In New England, for example, greater diversity would help alleviate the region's heavy reliance on natural gas, the supply of which has become constrained especially in winter months [4, 291]. As noted by ISO New England [291], "over-reliance on natural gas subjects the New England region to substantial price fluctuations that are influenced by a variety of market-based factors (i.e. exercising of natural gas contractual rights, tight gas spot-market trading), and technical factors (i.e. pipeline maintenance requirements and limited pipeline capacity)." DOE has also previously highlighted this issue in a 2004 report, stating: "To alleviate New England's volatile energy market and reduce its over-reliance on natural gas, the region needs to pursue an energy policy that is focused on fuel diversity. Increased use of renewable energy will enable New England to diversify the region's energy portfolio, thereby increasing electric reliability and lowering energy costs by utilizing local resources in the generation of electricity [292]." On the Atlantic, offshore wind tends to be winter-peaking, so it is well matched to compensate for cold-weather natural gas shortages.

Wind-Related Jobs and Local Economic Development

Due to its physical scale and local infrastructure requirements, offshore wind can bring significant wind-related jobs and local economic activity to coastal states, and government support for offshore wind has often hinged on these potential benefits [293, 294, 295, 296]. In 2012, Europe had approximately 58,000 workers employed in the offshore wind sector; the European Wind Industry Association notes that the industry, which barely existed a decade ago, has helped revitalize certain coastal cities as industrial hubs [297]. The same could be true in the United States. Studies of the potential local economic development and gross employment impacts of offshore wind in the United States include those by Keyser et al. [244], Flores et al. [242], and Navigant [240]. As discussed in Section 3.11, the offshore wind deployment envisioned in the *Study Scenario* results in an estimated 32,000–34,000 offshore wind-related jobs in 2020, increasing to 76,000–80,000 in 2030 and 170,000–181,000 in 2050.

Environmental Impacts and Siting Challenges

Offshore wind was formally introduced to the United States through the Energy Policy Act of 2005, known as EPAct. The Bureau of Ocean Energy Management was assigned regulatory jurisdiction, and stakeholders have cautiously welcomed offshore wind as a potential new member of the ocean use community. Nevertheless, some offshore wind projects have faced opposition from stakeholder groups that cite possible impacts ranging from degradation of the view-scape to avian mortality. As of 2014, carefully vetted offshore wind energy areas have emerged through federal and state marine spatial planning processes [298], especially in the Atlantic and Great Lakes. Relative to land-based projects in densely populated communities, large offshore wind projects can be located at sea, away from people, thereby potentially reducing the impacts to project neighbors from project construction and operation. There is also the potential that with projects located farther offshore, the risk to wildlife and sensitive environmental receptors such as birds and bats may be diminished as many sensitive ecosystems are closer to shore. Even far from shore, however, there are siting issues to address, including the migratory pathways, feeding, breeding, and nursery habitats of marine mammals as well as birds, bats, and fish (see Section 3.12).

3.13.2 Distributed Wind

Distributed wind applications, including customer-sited wind and wind turbines embedded in distribution networks, offer a number of unique benefits not otherwise analyzed in the *Wind Vision*. More specifically, distributed wind turbines give individuals and communities an opportunity to learn directly about wind power, empowering more localized discussion and growth for all wind power projects. The following sections highlight more examples of benefits resulting from distributed wind.

Economic Development

Distributed wind creates local economic development and job opportunities linked to the manufacturing, sales, installation, and maintenance of wind turbines used in distributed applications. Installation materials, services, and labor account for about 30% of the total installed cost for small wind turbines [299]. Domestic distributed wind investments in 2012 totaled $410 million. Of that amount, $101 million is attributed to the small wind turbine market segment, and an estimated $30 million of that value was therefore invested in installation materials, services, and labor from small turbines. U.S. suppliers dominate the domestic small wind turbine market, claiming 93% of 2013 sales on a unit basis and 88% on a capacity basis [15].U.S. small wind turbine suppliers also source most of their turbine components from domestic supply chain vendors, maintaining domestic content levels of 80–95% for turbine and tower hardware [300].

Utility Bill Reduction and Risk Protection

On-site distributed wind turbines allow farmers, schools, small businesses, and other energy users to benefit from reduced utility bills and predictable controlled costs and to hedge against the possibility of rising retail electricity rates. Once the wind system is paid off, the cost of the electricity produced is minimal, reflecting only the cost of ongoing maintenance. Distributed wind systems can also provide the owner with a sense of self-reliance.

The implementation of distributed wind on a community basis—whether through development by municipal utilities, local government organizations, or in isolated community power systems— can also provide wider community benefits of lower energy costs, higher reliability, and reduced sensitivity to fuel commodity prices. Of course, distributed wind is a highly location-dependent energy source, as its energy generation potential relies on the quality of the site's wind resource. The technology is therefore not appropriate for every community.

Electric Grid Benefits

Decentralized generation such as distributed wind can benefit the electrical grid. Distributed wind turbines installed in strategic locations can provide reactive power support and thereby benefit weak distribution grids that experience voltage-regulation problems [301]. Distributed wind systems may not require the construction of new transmission capacity, usually relying instead on available capacity on local distribution grids. In fact, distributed wind may at times lessen or mitigate a utility's need for distribution grid upgrades (if the output of such systems correlates well with the peak load on the distribution circuit), and it can help reduce transmission congestion [301]. While distributed wind systems utilize existing distribution grids, many distribution systems—particularly rural ones—would benefit from upgrades and modernization to improve their efficiency [302] and the integration of increasing amounts of distributed generation. This is true even though such upgrades could be costly. Utilities see the rise in distributed generation as both a threat to the traditional utility model as well as an opportunity for utility growth [303, 304].

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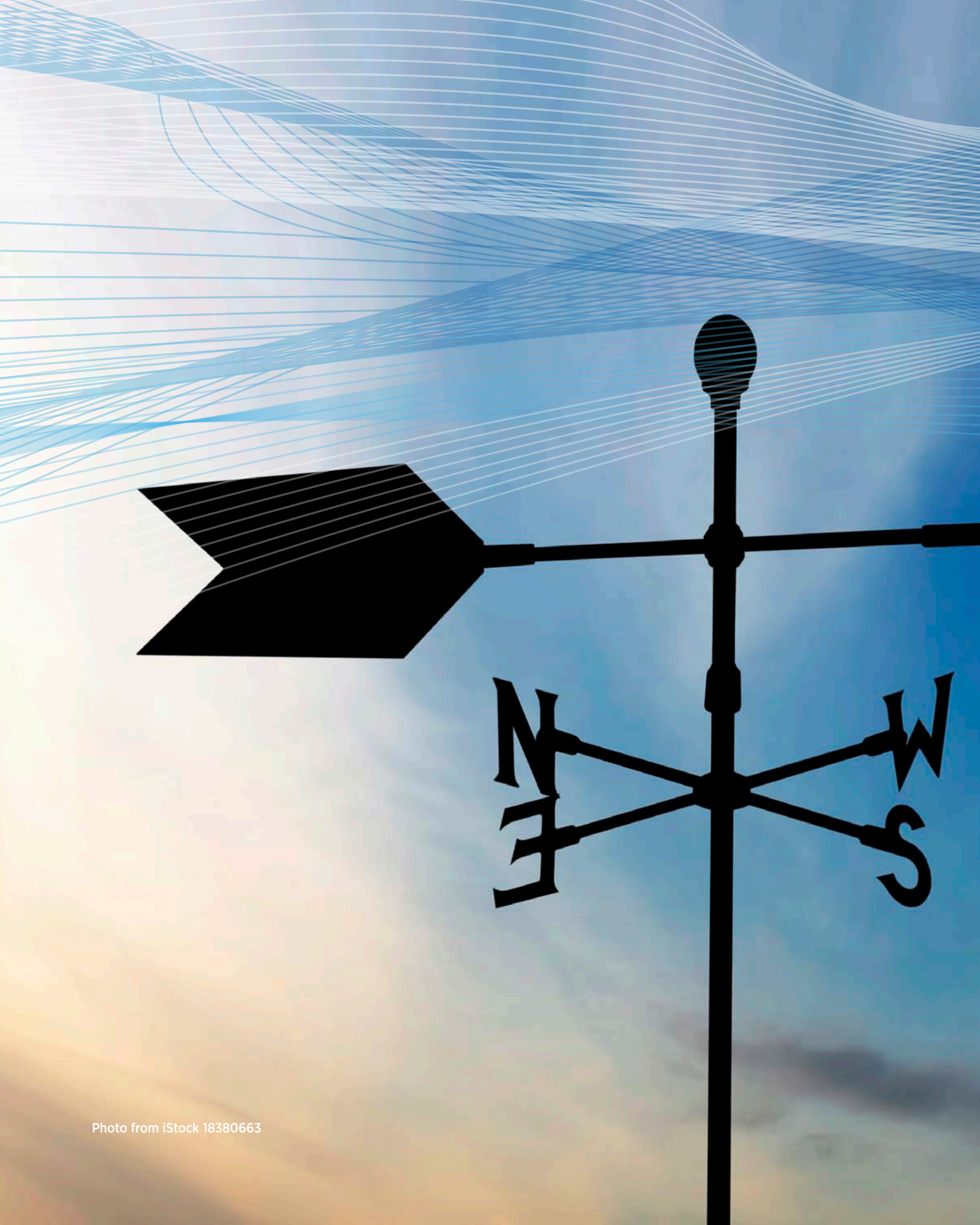

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4 The *Wind Vision* Roadmap: A Pathway Forward

Summary

Chapter 4 and Appendix M provide a detailed roadmap of technical, economic, and institutional actions by the wind industry, the wind research community, and others to optimize wind's potential contribution to a cleaner, more reliable, low-carbon, domestic energy generation portfolio, utilizing U.S. manufacturing and a U.S. workforce. The roadmap is intended to be the beginning of an evolving, collaborative, and necessarily dynamic process. It thus suggests an approach of continual updates at least every two years, informed by its analysis activities. Roadmap actions are identified in nine topical areas, introduced below.

Wind Power Resources and Site Characterization

Significant reductions in the cost of wind power can be achieved through improved understanding of the complex physics governing wind flow into and through wind plants. Better insight into the flow physics has the potential to guide technology advancements that could increase wind plant energy capture, reduce annual operating costs, and improve project financing terms to more closely resemble traditional capital projects.

Wind Plant Technology Advancement

Technology advancements can provide increased energy capture, lower capital and operating costs, and improved reliability. Sustained focus on the wind power plant as an integrated system will provide the proper context for such advancements. Many technology improvements can be developed as straightforward extensions of previously successful technology trends, while others will be the result of new innovations.

Supply Chain, Manufacturing, and Logistics

Achieving the *Wind Vision Study Scenario* cost and deployment levels, while also maximizing economic value to the nation, will require a competitive domestic manufacturing industry and supply chain capable of driving innovation and commercialization of new technologies. Such technologies will enable cost-effective production, transportation, construction, and installation of next-generation wind plants on land and offshore.

Wind Power Performance, Reliability and Safety

Wind power is becoming a mainstream, widespread technology. With this progress, asset owner/operators, utilities, and the public expect wind plants to meet the same operational reliability as conventional generation sources. While enormous progress has been made in reliability and availability of systems, significant reductions in overall cost of energy can still be realized through better operations and maintenance (O&M) practices. This is especially true in the offshore environment, where maintenance costs are significantly higher due to more difficult access.

Wind Electricity Delivery and Integration

Successfully addressing power system integration issues, while still maintaining electric power system reliability, is critical to achieving high wind penetrations at reasonable costs. Key issues in this area relate to increased variability and uncertainty posed by wind power at various time scales. Methods for managing the power system with moderate-to-high wind penetrations have evolved, and will likely continue to evolve as more actual experience is gained with wind power plants. Utilization of wind forecasting in operational practice of power systems and advanced controls on wind turbines can help operators decide on appropriate reserve levels. In some cases, operators will be able to deploy wind turbine and wind plant response capabilities to help manage the power system. Experience and research demonstrate that these approaches can be executed at reasonable cost if appropriate actions are taken.

Wind Siting and Permitting

As is true for any form of energy, wind power is associated with impacts to the natural surroundings. Wind is a comparatively clean source of energy with many positive attributes, such as no emissions, no air or water pollution, and no use of water in the generation of electricity. If improperly sited, however, wind power facilities may present socioeconomic, conflicting use, and environmental risks. Care needs to be taken in the siting of wind power facilities to ensure the potential for negative impacts from construction and operation is minimized to the greatest extent practicable.

Collaboration, Education and Outreach

Wind power development has experienced remarkable growth in terms of both deployment and technology innovation. The wind industry is seeing generational changes over the course of years, not decades, which can make it challenging for people not directly involved to stay abreast of this rapidly changing industry. Collaboration among domestic and international producers, researchers, and stakeholders during this time of rapid change facilitates learning about new approaches and technical advances that can lead to increased turbine performance, shorter deployment timelines, and lower overall costs.

Workforce Development

Realizing *Wind Vision Study Scenario* deployment levels and the associated benefits requires a robust and qualified workforce to support the industry throughout the product lifecycle. The industry needs a range of wind professionals, from specialized design engineers to installation and maintenance technicians, to enable the design, installation, operation, and maintenance of wind power systems. To support these needs, advanced planning and coordination are essential to educate a U.S. workforce from primary school through university degree programs.

Policy Analysis

Achieving wind power deployment to fulfill national energy, societal, and environmental goals—while minimizing the cost of meeting those goals—is likely to require practical and efficient policy mechanisms that support all three wind power markets: land-based, offshore, and distributed. Objective and comprehensive evaluation of different policy mechanisms is therefore needed, as are comparative assessments of the costs, benefits, and impacts of various energy technologies. Regular assessment of progress to enable ongoing prioritization of roadmap actions is also essential.

4.0 Introduction

Chapter 4 and Appendix M provide a detailed roadmap of technical, economic, and institutional actions by the wind industry, the wind research community, and others to optimize wind's potential contribution to a cleaner, more reliable, low-carbon, domestic energy generation portfolio, utilizing U.S. manufacturing and a U.S. workforce. This roadmap was developed through a collaborative effort led by the U.S. Department of Energy (DOE), with contributions and rigorous peer review from industry, the electric power sector, non-governmental organizations, academia, national labs, and other governmental participants. High-level roadmap actions are presented and discussed in this chapter. Most of these actions are augmented by more detailed actions, which are described in Appendix M.[1]

The roadmap is not prescriptive. It does not detail how suggested actions are to be accomplished; it is left to the responsible organizations to determine the optimum timing and sequences of specific activities. While the *Wind Vision* report informs policy options, it is beyond the scope of the *Wind Vision* roadmap to suggest policy preferences and no attempt is made to do so.

The *Wind Vision Study Scenario* projects that wind power costs continue to decline, that demand for wind power grows to support the *Study Scenario* penetration levels, and that wind power plants and the transmission assets needed to support them are actually built. In general, assumptions along these three lines are implicit in the *Study Scenario* modeling process. In aggregate, the roadmap actions are aimed at achieving the progress implied by these assumptions.

The Roadmap Approach

The *Wind Vision* roadmap outlines actions that can be taken by stakeholders under three distinct yet complementary themes designed to enable U.S. wind to compete for deployment in the U.S. power generation portfolio. The *Wind Vision* specifically does not make policy recommendations. By addressing market barriers, however, the *Wind Vision* roadmap actions can reduce the cost of complying with future proposed policy decisions and help improve market competitiveness of wind. The three key themes of the roadmap are:

1. **Reduce Wind Costs:** Chapter 3 demonstrates that the costs associated with the *Study Scenario* can be reduced across the range of sensitivities with wind cost reductions. Accordingly, reductions in levelized cost of electricity are a priority focus. This theme includes actions to reduce capital costs; reduce annual operating expenses; optimize annual energy production and reduce curtailment and system losses; reduce financing expenses; reduce grid integration and operating expenses; and reduce market barrier costs including regulatory and permitting, environmental, and radar mitigation costs.
2. **Expand Developable Areas:** Expansion of wind power into high-quality resource areas is also important for realizing the *Study Scenario* at cost levels described in Chapter 3 of the *Wind Vision* report. Key actions within this theme include actions to responsibly expand transmission and developable geographic regions and sites; improve the potential of low wind speed locales; improve the potential of ocean and Great Lakes offshore regions; and improve the potential in areas requiring careful consideration of wildlife, aviation, telecommunication, or other environmental issues. National parks, densely populated locations, and sensitive areas such as federally designated critical habitat are generally excluded from the roadmap actions, since they are likely not to be developed as wind sites.

1. The majority of the actions described in this chapter and Appendix M address utility-scale wind power, both land-based and offshore. DOE and the distributed wind community are assessing the prospects and development needs for distributed wind power. While several actions addressing distributed wind are included in the *Wind Vision* roadmap, the ongoing assessment is expected to generate a more complete set of distributed wind actions.

3. **Increase Economic Value for the Nation:** The *Study Scenario* projects substantial benefits for the nation, but additional steps are needed to ensure that these benefits are realized and maximized. This theme includes actions to provide detailed and accurate data on costs and benefits for decision makers; grow and maintain U.S. manufacturing throughout the supply chain; train and hire the U.S. workforce; provide diversity in the electricity generation portfolio; and provide a hedge against fossil fuel price increases. The overall aim is to ensure that wind power continues to provide enduring value for the nation.

The roadmap actions are intentionally limited to extensions and improvements of existing technologies and do not include transformational innovations. These innovations may occur, but, because of their novel nature, it is not possible to prescribe how to appropriately leverage them in advance in a roadmap process.

The roadmap is intended to be the beginning of an evolving, collaborative, and necessarily dynamic process. It thus suggests an approach of continual updates at least every two years, informed by its analysis activities. These periodic reviews will assess effects and redirect activities as necessary and appropriate through 2050 to optimize adaptation to changing technology, markets and political factors. High-level roadmap areas are summarized in Table 4-1 and the related high-level actions are summarized in Text Box 4-1. Appendix M provides a more granular description of the roadmap actions, including potential stakeholders and possible timelines for action.

Risk of Inaction

The analytical results of Chapter 3 reveal significant overall cumulative job, health, carbon, environmental, and other social benefits at deployment levels in the *Wind Vision Study Scenario*. Reduced economic activity and increased energy efficiency measures have slowed the growth of electricity demand and reduced the need for new generation of any kind. This decreased need for new generation, in combination with decreased natural gas costs and other factors, has reduced demand for new wind plants. These forces may cause the near-term U.S. market for wind equipment to fall below levels that will support a continued robust domestic manufacturing supply chain. If wind installation rates decline significantly, wind's ongoing contributions to U.S. economic development and U.S. manufacturing will likely be at risk. Wind operations will continue, but manufacturing will remain vibrant only as long as there are domestic markets to serve. If domestic markets for new installations deteriorate, manufacturing may move to other active regions of the world.

Table 4–1. *Wind Vision* Roadmap Strategic Approach Summary

Core Challenge	Wind has the potential to be a significant and enduring contributor to a cost-effective, reliable, low carbon, U.S. energy portfolio. Optimizing U.S. wind power's impact and value will require strategic planning and continued contributions across a wide range of participants.		
Key Themes	**Reduce Wind Costs** Collaboration to reduce wind costs through wind technology capital and operating cost reductions, increased energy capture, improved reliability, and development of planning and operating practices for cost-effective wind integration.	**Expand Developable Areas** Collaboration to increase market access to U.S. wind resources through improved power system flexibility and transmission expansion, technology development, streamlined siting and permitting processes, and environmental and competing use research and impact mitigation.	**Increase Economic Value for the Nation** Collaboration to support a strong and self-sustaining domestic wind industry through job growth, improved competitiveness, and articulation of wind's benefits to inform decision making.
Issues Addressed	Continuing declines in wind power costs and improved reliability are needed to improve market competition with other electricity sources.	Continued reduction of deployment barriers as well as enhanced mitigation strategies to responsibly improve market access to remote, low wind speed, offshore, and environmentally sensitive locations.	Capture the enduring value of wind power by analyzing job growth opportunities, evaluating existing and proposed policies, and disseminating credible information.
Wind Vision Study Scenario Linkages	Levelized cost of electricity reduction trajectory of 24% by 2020, 33% by 2030, and 37% by 2050 for land-based wind power technology and 22% by 2020, 43% by 2030, and 51% by 2050 for offshore wind power technology to substantially reduce or eliminate the near- and mid-term incremental costs of the *Study Scenario*.	Wind deployment sufficient to enable national wind electricity generation shares of 10% by 2020, 20% by 2030, and 35% by 2050.	A sustainable and competitive regional and local wind industry supporting substantial domestic employment. Public benefits from reduced emissions and consumer energy cost savings.
Roadmap Action Areas[a]	• Wind Power Resources and Site Characterization • Wind Plant Technology Advancement • Supply Chain, Manufacturing, and Logistics • Wind Power Performance, Reliability, and Safety • Wind Electricity Delivery and Integration • Wind Siting and Permitting • Collaboration, Education, and Outreach • Workforce Development • Policy Analysis	• Wind Power Resources and Site Characterization • Wind Plant Technology Advancement • Supply Chain, Manufacturing, and Logistics • Wind Electricity Delivery and Integration • Wind Siting and Permitting • Collaboration, Education, and Outreach • Policy Analysis	• Supply Chain, Manufacturing, and Logistics • Collaboration, Education, and Outreach • Workforce Development • Policy Analysis

a. Several action areas address more than one key theme.

Text Box 4–1.

High-Level Wind Vision Roadmap Actions

1 Wind Power Resources and Site Characterization

Action 1.1 – Improve Wind Resource Characterization. Collect data and develop models to improve wind forecasting at multiple temporal scales—e.g., minutes, hours, days, months, years.

Action 1.2 – Understand Intra-Plant Flows. Collect data and improve models to understand intra-plant flow, including turbine-to-turbine interactions, micro-siting, and array effects.

Action 1.3 – Characterize Offshore Wind Resources. Collect and analyze data to characterize offshore wind resources and external design conditions for all coastal regions of the United States, and to validate forecasting and design tools and models at heights at which offshore turbines operate.

2 Wind Plant Technology Advancement

Action 2.1 – Develop Next-Generation Wind Plant Technology. Develop next-generation wind plant technology for rotors, controls, drivetrains, towers, and offshore foundations for continued improvements in wind plant performance and scale-up of turbine technology.

Action 2.2 – Improve Standards and Certification Processes. Update design standards and certification processes using validated simulation tools to enable more flexibility in application and reduce overall costs.

Action 2.3 – Improve and Validate Advanced Simulation and System Design Tools. Develop and validate a comprehensive suite of engineering, simulation, and physics-based tools that enable the design, analysis and certification of advanced wind plants. Improve simulation tool accuracy, flexibility, and ability to handle innovative new concepts.

Action 2.4 – Establish Test Facilities. Develop and sustain world-class testing facilities to support industry needs and continued innovation.

Action 2.5 – Develop Revolutionary Wind Power Systems. Invest research and development (R&D) into high-risk, potentially high-reward technology innovations.

3 Supply Chain, Manufacturing and Logistics

Action 3.1 – Increase Domestic Manufacturing Competitiveness. Increase domestic manufacturing competitiveness with investments in advanced manufacturing and research into innovative materials.

Action 3.2 – Develop Transportation, Construction, and Installation Solutions. Develop transportation, construction and installation solutions for deployment of next-generation, larger wind turbines.

Action 3.3 – Develop Offshore Wind Manufacturing and Supply Chain. Establish domestic offshore manufacturing, supply chain, and port infrastructure.

4 Wind Power Performance, Reliability, and Safety

Action 4.1 – Improve Reliability and Increase Service Life. Increase reliability by reducing unplanned maintenance through better design and testing of components, and through broader adoption of condition monitoring systems and maintenance.

Action 4.2 – Develop a World-Class Database on Wind Plant Operation under Normal Operating Conditions. Collect wind turbine performance and reliability data from wind plants to improve energy production and reliability under normal operating conditions.

Action 4.3 – Ensure Reliable Operation in Severe Operating Environments. Collect data, develop testing methods, and improve standards to ensure reliability under severe operating conditions including cold weather climates and areas prone to high force winds.

Action 4.4 – Develop and Document Best Practices in Wind O&M. Develop and promote best practices in operations and maintenance (O&M) strategies and procedures for safe, optimized operations at wind plants.

Action 4.5 – Develop Aftermarket Technology Upgrades and Best Practices for Repowering and Decommissioning. Develop aftermarket upgrades to existing wind plants and establish a body of knowledge and research on best practices for wind plant repowering and decommissioning.

Continues next page

Text Box 4-1.

High-Level Wind Vision Roadmap Actions *(continued)*

5 Wind Electricity Delivery and Integration

Action 5.1 – Encourage Sufficient Transmission. Collaborate with the electric power sector to encourage sufficient transmission to deliver potentially remote generation to electricity consumers and provide for economically efficient operation of the bulk power system over broad geographic and electrical regions.

Action 5.2 – Increase Flexible Resource Supply. Collaborate with the electric power sector to promote increased flexibility from all resources including conventional generation, demand response, wind and solar generation, and storage.

Action 5.3 – Encourage Cost-Effective Power System Operation with High Wind Penetration. Collaborate with the electric power sector to encourage operating practices and market structures that increase cost-effectiveness of power system operation with high levels of wind power.

Action 5.4 – Provide Advanced Controls for Grid Integration. Optimize wind power plant equipment and control strategies to facilitate integration into the electric power system, and provide balancing services such as regulation and voltage control.

Action 5.5 – Develop Optimized Offshore Wind Grid Architecture and Integration Strategies. Develop optimized subsea grid delivery systems and evaluate the integration of offshore wind under multiple arrangements to increase utility confidence in offshore wind.

Action 5.6 – Improve Distributed Wind Grid Integration. Improve grid integration of and increase utility confidence in distributed wind systems.

6 Wind Siting and Permitting

Action 6.1 – Develop Mitigation Options for Competing Human Use Concerns. Develop impact reduction and mitigation options for competing human use concerns such as radar, aviation, maritime shipping, and navigation.

Action 6.2 – Develop Strategies to Minimize and Mitigate Siting and Environmental Impacts. Develop and disseminate relevant information as well as minimization and mitigation strategies to reduce the environmental impacts of wind power plants, including impacts on wildlife.

Action 6.3 – Develop Information and Strategies to Mitigate the Local Impact of Wind Deployment and Operation. Continue to develop and disseminate accurate information to the public on local impacts of wind power deployment and operations.

Action 6.4 – Develop Clear and Consistent Regulatory Guidelines for Wind Development. Streamline regulatory guidelines for responsible project development on federal, state, and private lands, as well as in offshore areas.

Action 6.5 – Develop Wind Site Pre-Screening Tools. Develop commonly accepted standard siting and risk assessment tools allowing rapid pre-screening of potential development sites.

7 Collaboration, Education, and Outreach

Action 7.1 – Provide Information on Wind Power Impacts and Benefits. Increase public understanding of broader societal impacts of wind power, including economic impacts; reduced emissions of carbon dioxide, other greenhouse gases, and chemical and particulate pollutants; less water use; and greater energy diversity.

Action 7.2 – Foster International Exchange and Collaboration. Foster international exchange and collaboration on technology R&D, standards and certifications, and best practices in siting, operations, repowering, and decommissioning.

8 Workforce Development

Action 8.1 – Develop Comprehensive Training, Workforce, and Educational Programs. Develop comprehensive training, workforce, and education programs, with engagement from primary schools through university degree programs, to encourage and anticipate the technical and advanced-degree workforce needed by the industry.

9 Policy Analysis

Action 9.1 – Refine and Apply Energy Technology Cost and Benefit Evaluation Methods. Refine and apply methodologies to comprehensively evaluate and compare the costs, benefits, risks, uncertainties, and other impacts of energy technologies.

Action 9.2 – Refine and Apply Policy Analysis Methods. Refine and apply policy analysis methodologies to understand federal and state policy decisions affecting the electric sector portfolio.

Action 9.3 – Maintain the Roadmap as a Vibrant, Active Process for Achieving the Wind Vision Study Scenario. Track wind technology advancement and deployment progress, prioritize R&D activities, and regularly update the wind roadmap.

4.1 Wind Power Resources and Site Characterization

Significant reductions in the cost of wind power can be achieved through improved understanding of the complex physics governing wind flow into and through wind plants. Better insight into the flow physics has the potential to guide technology advancements that could increase wind plant energy capture [1], reduce annual operational costs, and improve project financing terms to more closely resemble traditional capital projects.

Realizing these opportunities will require diverse expertise and substantial resources, including high fidelity modeling and advanced computing. In order to validate new and existing high fidelity simulations, several experimental measurement campaigns across different scales will be required to gather the necessary data. These may include wind tunnel tests, scaled field tests, and large field measurement campaigns at operating plants. The data required include long-term atmospheric data sets, wind plant inflow, intra-wind plant flows (e.g., wakes), and rotor load measurements. Such measurement campaigns will be essential to addressing wind energy resource and site characterization issues and will yield improvements in models that bridge the applicable spatial-temporal scales.

Innovations in sensors such as Light Detection and Ranging, or LIDAR[2]; Sonic Detection and Ranging, or SODAR; wind profiling radars; and other new, high-fidelity instrumentation will also be needed to successfully collect data at the resolutions necessary to validate high-fidelity simulations. Significant effort will be required to store simulation results and data sets, enabling additional research and analysis in a user-friendly and publicly accessible database.

Resource characterization needs can be generally categorized in terms of increasing temporal and spatial scales:

- **Turbine dynamics**—representing phenomena such as turbulence and shear at the scale important to individual turbine inflow;
- **Micro-siting and array effects**—characterizing complex localized flows including terrain and turbine wake effects to optimize siting of turbines within projects and accurately predict power output;
- **Mesoscale processes**—representing wind fields across regional or mesoscale areas in the actual and forecasting timeframes important for operation of the electric power grid; and
- **Climate effects**—accounting for the effects of climate change and climate variability to protect long-term investments in wind power and other infrastructure.

More and better observations, improved modeling at all four spatial and temporal scales, and an integrated bridging of the four spatial-temporal scales are needed. *Research Needs for Wind Resource Characterization* [2] describes this topic in more detail.

The following actions focus on three key objectives:

- **Improving fundamental wind resource characterization to reduce the error and uncertainty of wind forecasts;**
- **Understanding intra-plant flows to optimize wind plant output; and**
- **Using data and analysis to devise offshore-specific wind resource characterization to better understand marine design and operating conditions.**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.1.

2. Remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light.

Action 1.1: Improve Wind Resource Characterization

Improved characterization and understanding of wind resources are essential to increasing wind plant revenue and operating cost performance, thereby reducing risks to developers. This will contribute to reducing the cost of wind power and improve cost competition in the electricity sector.

ACTION 1.1: Improve Wind Resource Characterization	
Collect data and develop models to improve wind forecasting at multiple temporal scales—e.g., minutes, hours, days, months, years.	
DELIVERABLE	**IMPACT**
Data, validated models, and measurement techniques that improve ability to predict wind plant power output over several spatial and temporal scales.	Increased wind plant performance resulting in increased revenue, improved reliability, and decreased operating costs.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore	

Reducing the error and uncertainty of wind resource forecasts and wind power generation facilitates integration of wind into the electric grid. Stakeholder action is needed to develop, validate, and apply models and measurement techniques that accurately characterize and forecast the wind in various time frames—e.g., minutes, hours, days, months, years. Forecasts on the hourly scale support dispatch decisions, multi-hour forecasts warn of ramp events (rapid changes in power output), and day-ahead forecasts inform unit-commitment decisions. Two primary aspects of Numerical Weather Prediction are the data assimilation scheme and the model physics, both of which can be improved through stakeholder action to support wind integration.

Action 1.2: Understand Intra-Plant Flows

An improved understanding of the aerodynamic environment within a wind plant, including turbine-to-turbine interaction, is needed to optimize wind plant power production. Incorrect simulations of intra-plant flows can indirectly result in wind plant energy losses from wakes, complex terrain, and turbulence, as well as unknown turbine loading conditions that can result in over-designed turbine components.

High performance computational capability has recently become available to explore these issues [3], providing major opportunities to gain insight through advanced, high-fidelity modeling. For example, the High Performance Computing Data Center at the DOE's National Renewable Energy Laboratory provides high-speed, large-scale computer processing to advance research on renewable energy and energy efficiency technologies. Through computer modeling and simulation, researchers can explore processes and technologies that cannot be directly observed in a laboratory or that are too expensive or too time-consuming to be conducted otherwise [4].

ACTION 1.2: Understand Intra-Plant Flows	
Collect data and improve models to understand intra-plant flow, including turbine-to-turbine interactions, micro-siting, and array effects.	
DELIVERABLE	**IMPACT**
Data, validated models and measurement techniques to minimize turbulence induced by adjacent turbines through optimized siting.	Increased wind plant energy production and reduced turbine maintenance requirements.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore	

Action 1.3: Characterize Offshore Wind Resources

Meteorological and oceanographic (metocean) data are integral to defining the design and operating conditions over the lifetimes of offshore wind projects in regions where they may be sited. Construction and maintenance planning is dependent on known sea states (wave height, period, and power spectrum) and on the availability of accurate forecasts. In the United States, observational metocean data are sparsely collected and relies heavily on surface weather buoys that cannot probe hub height wind conditions. Significant portions of the oceans and Great Lakes lack year-round observational data and rely on models to estimate metocean conditions. These gaps cause a high level of uncertainty associated with the offshore resource and design environment; this in turn imposes additional cost and risk to offshore wind projects. Characterizing the metocean conditions through a series of measurement and modeling approaches targeted specifically for offshore wind power applications and the broad stakeholder community will help address these challenges.

ACTION 1.3: Characterize Offshore Wind Resources	
Collect and analyze data to characterize offshore wind resources and external design conditions for all coastal regions of the United States, and to validate forecasting and design tools and models at heights at which offshore turbines operate.	
DELIVERABLE	**IMPACT**
Resource maps, forecasting tools, weather models, measurement stations, and technical reports documenting physical design basis.	Improved offshore R&D strategy and accelerated offshore wind deployment.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Offshore	

4.2 Wind Plant Technology Advancement

Technology advancements can provide increased energy capture, lower capital and operational costs, and improved reliability. Sustained focus on the wind power plant as an integrated system will provide the proper context for these advances in technology. Many of these advances can be developed as straightforward extensions of previously successful technology trends, while others will be the result of new innovations.

The time and cost required to develop and certify new technology are substantial. To be successful, a consistent effort with many contributors is required. This reinforces the value of domestic and international partnerships that can bring together the resources necessary to fully realize opportunities for advanced technology.

Five key actions will support technology advancement:

- **Developing advanced wind plant sub-systems such as larger rotors;**
- **Updating design and certification standards to improve the certification process;**
- **Developing and validating comprehensive simulation tools to guide wind plant technology development;**
- **Developing and sustaining publicly available test facilities to verify the performance and reliability of new technology; and**
- **Devising a structured process to systematically identify and develop revolutionary concepts and invest R&D into potentially high-reward innovation.**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.2.

Action 2.1: Develop Next-Generation Wind Plant Technology

The substantial advances in wind plant technology since 2008 illustrate the importance of technological innovation. Continued advances in technology will provide lower costs for wind power, increased deployment opportunities at lower wind speed sites, new offshore technology for both shallow and deep water, and improved reliability.

Innovations are needed that facilitate continued growth in the size and capacity of wind turbine systems. Opportunities for advancement exist in rotors, control systems, drivetrains, towers, and offshore foundations.

ACTION 2.1: Develop Next-Generation Wind Plant Technology	
Develop next-generation wind plant technology for rotors, controls, drivetrains, towers, and offshore foundations for continued improvements in wind plant performance and scale-up of turbine technology.	
DELIVERABLE	**IMPACT**
Wind power systems with lower cost of energy.	Reduced energy costs for U.S. industry and consumers. Increased wind deployment nationwide.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore	

Much larger rotors per installed megawatt (MW) are needed to continue expanding the range of sites across the United States that can produce wind power at a competitive price. Rotor blades that can be delivered to a wind plant in two or more pieces and assembled on-site will enable the continued growth of rotor diameters. Additional opportunities for innovation in the design of blades include aeroelastic design techniques that shed loads; advanced low-cost, high-strength materials; and active or passive aerodynamic and noise control devices.

Sophisticated turbine control systems will continue to contribute to increases in energy capture and the reduction of structural loads. Techniques that measure the wind upstream of individual turbines and wind plants, such as LIDAR, provide more accurate information about the flow field and allow control systems to take action before changes in the wind reach the turbines. Important opportunities are available in aerodynamic control to reduce structural loads using independent blade pitch control, as well as aerodynamic devices along the span of the blade. Wind plant control systems are evolving to operate the plant in an integrated manner, ensuring maximum energy capture, highest overall plant reliability, and active control of the plant's electrical output to provide ancillary services and support grid stability and reliability. In many cases, these improvements can be added with little or no increase in cost.

Continued development is needed to reduce cost and improve reliability and efficiency of the drivetrains and power conversion systems that turn the rotor's rotational power into electrical power. Conventional multi-stage geared approaches, medium-speed systems, and direct-drive architectures each have advantages, and technological development of all three configurations should be continued. High-flux permanent magnets can improve the efficiency of these configurations, and efforts to develop alternatives to the existing rare-earth technologies should be undertaken. New materials for power conversion electronics, such as silicon carbide, can increase efficiency and eliminate the need for complex liquid cooling systems.

Taller towers are the necessary complement to larger rotors. Taller towers also provide access to the stronger winds that exist at higher elevations and are a key enabler for cost-effective development of lower wind speed sites. Logistics constraints, however, limit the maximum diameter of tower sections that can be transported over land, and this causes the cost of tall towers to increase disproportionately. Innovations that permit increased on-site assembly of towers are needed.

The fabrication and installation costs of offshore foundations and support structures are higher than comparable costs for land-based wind. Offshore costs can be lowered considerably by reducing construction time and dependency on costly heavy-lift vessels, as well as through technology innovations, mass production, and standardization of the support structure. This opportunity will guide the development of advanced offshore foundations and substructures.

More than 60% of the gross U.S. resource potential for offshore wind is over water deeper than 60 meters [5]. At these depths, the cost of fixed-bottom substructures increases rapidly in comparison to shallower waters. Floating offshore wind turbine platforms may be more cost effective in these deep waters. New floating platform technologies should be developed with equivalent or lower costs than those of existing fixed-bottom systems. New technologies to mitigate high dynamic loading on the tower and support structure (imposed by flowing winter ice sheets) can enable development of up to 500 gigawatts (GW) of gross offshore wind resource potential in the Great Lakes. Hurricanes frequently affect the U.S. coastline from Cape Cod, Massachusetts, to Galveston, Texas, as well as Hawaii—affecting more than 1,000 GW of gross offshore wind resource area. New design approaches and operating strategies should be developed that can protect offshore wind turbines and foundations against these extreme events.

Action 2.2: Improve Standards and Certification Processes

The development in the 1990s of widely accepted international standards for the certification of wind power systems led to increased reliability, lower costs, and improved investor confidence. This was a key advancement that enabled the large-scale wind deployment that has occurred since the early 2000s.

ACTION 2.2: Improve Standards and Certification Processes	
Update design standards and certification processes using validated simulation tools to enable more flexibility in application and reduce overall costs.	
DELIVERABLE	**IMPACT**
Certification processes that provide the required level of reliability while remaining flexible and inexpensive.	Lower overall costs, increased reliability, and reduced barriers to deployment.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore, Distributed	

These standards, however, were developed in an era when simulation tools for wind power systems had limited capabilities. Turbine technology has evolved substantially since then, from relatively simple constant-speed, stall-regulated turbines that produced a few hundred kilowatts to modern, vastly larger and more sophisticated multi-MW turbines that use variable speed and full-span pitch control to limit structural loads and improve performance. This history has led to conservatism in the present generation of standards that may increase costs unnecessarily.

Making reliability a foundation of the next generation of standards should provide designers and manufacturers the flexibility to alter systems for optimization in specific sites, without excessive recertification costs or delays. Updated certification standards can be developed using a comprehensive process that measures structural loads and validates the accuracy of the industry's simulation tools for the full range of operational conditions experienced over the lifecycle of wind systems. These simulation tools will need to properly account for the operational environment in the interior of a wind plant using the complex flow data described in Section 4.1, *Wind Power Resources and Site Characterization*.

As of 2013, industry standards for offshore wind did not specifically address the design of structures in regions prone to tropical cyclones (hurricanes). This is a potential impediment to the development of more than 1,000 GW of offshore resources. New standards and engineering approaches are needed to design reliable offshore wind plants in light of risk of exposure to hurricanes. Combined wind, wave, and current data should be gathered during the passage of a hurricane to better define the operational environment. Detailed simulations of the structural response of the wind turbine and foundation during the passage of hurricanes should be completed to inform comprehensive design standards, and aerodynamic and structural data should be gathered on an operational turbine in a hurricane to validate these simulation results. Research is needed on the effect of hurricane conditions on wind plant capital and operational costs in order to optimize structural reliability provided by the standards and minimize lifecycle costs.

Developing and achieving consensus on revised international standards for the certification of wind power systems takes many years. Development of the next generation of standards will require collaboration among the wind industry, research laboratories, and national authorities around the world. Coordination with national, state, and local permitting processes is required to harmonize the new standards with the many authorities having jurisdiction over the permitting process.

Action 2.3: Improve and Validate Advanced Simulation and System Design Tools

Wind power system simulation tools, which are vital to modern engineering design and analysis, continue to see dramatic improvements in capability and accuracy. These improvements have reduced product development time and cost by largely eliminating the need for extensive redesign after initial testing. The need for these computer-aided physics and engineering tools to help reduce cost, increase reliability, and extend system lifetime will continue as wind deployment accelerates.

ACTION 2.3: Improve and Validate Advanced Simulation and System Design Tools	
Develop and validate a comprehensive suite of engineering, simulation, and physics-based tools that enable the design, analysis and certification of advanced wind plants. Improve simulation tool accuracy, flexibility, and ability to handle innovative new concepts.	
DELIVERABLE	**IMPACT**
Reliably accurate predictions of all characteristics of existing and novel wind turbine and wind plant configurations.	Improved technical and economic performance, increased reliability, and reduced product development cycle time.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore, Distributed	

A first step should be a comprehensive validation campaign to define the accuracy, strengths, and weaknesses of today's simulation tools for a wide range of modern wind power systems. This effort is directly supportive of the work described in Action 2.2 to develop next-generation certification standards, and will simultaneously support the identification of key opportunities and needs for improvements in the suite of simulation tools. Academia, research laboratories, and the wind industry can then collaborate to develop the improvements identified in the validation campaign. Rigorous assessment of simulation capabilities should be repeated periodically as the size and configuration of next-generation wind power systems evolve.

The focus of simulation tool development has been moving away from individual turbines and toward the challenge of simulating a complete wind plant (i.e., Simulator for Wind Farm Applications, or SOWFA; and Wind-Plant Integrated System Design & Engineering Model, or WISDEM).[3] This trend should be continued and accelerated. Improved simulation capabilities for the wind plant as a system enable further reductions in cost as well as improvements in performance. The ability to address the entire wind plant has been enabled by continued advances in capability and reductions in cost for high-performance computing systems.

Simulation tools under development can facilitate design of wind plants with significant gains in energy production and reduced structural loads. Flexible simulation tools should be created to support the design and development of innovative configurations for wind power systems. The ability to reliably simulate the operation of new configurations is a foundational capability for a successful innovation process.

Action 2.4: Establish Test Facilities

The performance and reliability of wind power systems need to be verified prior to deployment. This verification process is a key element of the overall risk management strategy, and is a requirement for certification. Test facilities also play an essential role in the development of new technologies. Current test facilities provide substantial capability, but increased capabilities are needed to support the continued growth of wind power.

3. Learn more about SOWFA at *https://nwtc.nrel.gov/SOWFA*, and more about WISDEM at *http://www.nrel.gov/wind/systems_engineering/models_tools.html*.

ACTION 2.4: Establish Test Facilities	
Develop and sustain world-class testing facilities to support industry needs and continued innovation.	
DELIVERABLE	**IMPACT**
Cost-effective, publicly available test facilities for all critical wind plant subsystems.	Lower cost of energy from increased reliability, reduced product development time, and support of innovative technology development.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore	

Wind power systems have grown to a scale at which test facilities become costly to develop and maintain. Shared facilities provide a cost-effective capability for the entire industry. Recently established facilities for the testing of blades (the Massachusetts Clean Energy Center's Wind Technology Testing Center) and drivetrains (dynamometers at the National Renewable Energy Laboratory and Clemson University) provide excellent examples of this approach.

As turbines have grown in size and capacity, it has become challenging to conduct field testing at appropriate sites. Industry manufacturers often use privately owned facilities for testing. In addition, the National Wind Technology Center near Boulder, Colorado, provides field testing at a site with strong and turbulent winds that are well characterized. The National Wind Technology Center site also has a Controllable Grid Interface that allows for the testing of wind turbines when anomalous grid conditions are present. Expansion of this field testing site would be necessary to meet the needs of the coming generation of much larger wind turbines. The field testing facility at Texas Tech University near Lubbock, Texas, provides a complementary field testing capability with lower turbulence and without the complex terrain of the National Wind Technology Center, and further expansion of this site would support larger turbines.

The Scaled Wind Farm Technology facility at the Texas Tech University site, known as SWiFT, provides an important capability to test turbine-to-turbine aerodynamic interactions at a small scale. Establishment of a similar facility to support testing at full scale would support continued wind growth. Installing research-grade instrumentation at an existing operational wind plant could provide an efficient approach for establishing a full-scale facility for measuring aerodynamic interactions. There is also a need for test facilities to validate innovative wind turbine and wind plant technologies at ultra-large scales and under unique offshore environmental conditions.

Other wind system test facilities exist in addition to those above. No publicly available facilities exist in the United States, however, to support testing of the many subsystems in a wind turbine and wind plant. The complex interactions between subsystems are frequently the root cause of reliability issues. A dedicated test facility could provide the capabilities to examine these interactions in a realistic and controlled environment.

Action 2.5: Develop Revolutionary Wind Power Systems

In the early days of the wind industry, a wide variety of configurations was developed and deployed. These configurations included both upwind and downwind rotors, various numbers of rotor blades, horizontal and vertical axis machines, and a variety of power conversion subsystems. Turbines with a horizontal axis rotor and three blades operating upwind of a tubular tower, with full-span blade pitch control and variable rotor speed, became the dominant configuration because of the excellent performance and reliability provided by this arrangement. Several decades of advancement in this configuration has given it a strong position in the marketplace.

Alternative configurations have been proposed that could provide advantages over the existing technology. Examples of these new configurations include floating vertical axis turbines, shrouded horizontal axis turbines, turbines with rotors that operate downwind of the tower, and airborne wind power systems. The cost and time to develop new wind turbine configurations at MW-scale, however, make it difficult for such innovations to enter the marketplace.

ACTION 2.5: Develop Revolutionary Wind Power Systems	
Invest R&D into high-risk, potentially high-reward technology innovations.	
DELIVERABLE	**IMPACT**
A portfolio of alternative wind power systems with the potential for revolutionary advances.	Lower cost of energy, mitigation of deployment barriers.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore	

Public-private partnerships could be created to facilitate the multi-year, high-risk development process needed for these new technologies. A structured innovation process that identifies and provides solutions for the fundamental wind power conversion processes has the potential to provide a robust framework for this effort. Promising technologies should be demonstrated at increasing scale in a series of laboratory and field tests. The development of flexible simulation tools discussed previously is a critical enabler for this innovation. To ensure long-term success, support for this effort would need to transition from public to private sources as commercial prospects grow.

4.3 Supply Chain, Manufacturing, and Logistics

Achieving the *Wind Vision Study Scenario* for cost and deployment while also maximizing the economic value to the nation will require a competitive domestic manufacturing industry and supply chain capable of driving innovation and commercialization of new technologies. Such technologies will enable cost-effective production, transportation, construction, and installation of next-generation wind plants on land and offshore.

As described in Chapter 2, the U.S wind industry has enjoyed robust growth. An average of 7 GW per year was installed during the period from 2007 to 2013, hitting a peak of 13 GW installed in 2012, while the share of domestically produced components simultaneously increased. These manufacturing and installation trends demonstrate sufficient capability in the global wind industry to meet the levels of deployment presented in the *Wind Vision*. What is less certain is where next-generation wind power technology will be developed, where it will be manufactured, and whether the necessary infrastructure and technology will be available to transport and construct it both on land and offshore. Capturing the economic value to the nation will require a collective set of actions to be taken by a variety of stakeholders including industry, government, and academic and other research institutions to enhance and sustain a globally competitive domestic supply chain.

The following are key actions that build on the past accomplishments of the U.S. manufacturing, transportation, and construction industries:

- **Invest in advanced manufacturing and research in order to increase domestic manufacturing competitiveness;**
- **Develop transportation, construction, and installation solutions that support next-generation wind technologies; and**
- **Establish a domestic offshore manufacturing and supply chain.**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.3.

Action 3.1: Increase Domestic Manufacturing Competitiveness

Given the continued increase in the size of wind components and the associated transportation limitations, the primary driver for a sustainable domestic supply chain is sufficient and consistent domestic demand for wind power—a key characteristic of the *Wind Vision Study Scenario*. Given this need for strong domestic demand, the question then becomes, "How can the U.S. supply chain capture the most economic value?" In industries with a global supply chain, such as wind, the value capture that a country realizes depends on the level of domestic content as shown in Chapter 2, section 2.4 of the *Wind Vision* report (*Economic and Social Impacts of Wind for the Nation*). This value also depends on the headquarters and R&D locations of the turbine and component manufacturers, who bring added profit margin on the product, provide additional jobs, and serve as a source of innovation to build and maintain global competitiveness [6].

ACTION 3.1: Increase Domestic Manufacturing Competitiveness	
Increase domestic manufacturing competitiveness with investments in advanced manufacturing and research into innovative materials.	
DELIVERABLE	**IMPACT**
New information, analysis tools, and technology to develop cost-competitive, sustainable, domestic wind power supply chain.	Reduced capital cost components, increased domestic manufacturing jobs and capacity, increased domestic technological innovation, and economic value capture.
Key Themes: Reduce Wind Costs; Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

The large size of major wind components makes them subject to transportation constraints and therefore suitable for domestic manufacture. Improving the competitiveness of the U.S. supply chain requires thorough analysis to understand the cost structure of U.S. and foreign suppliers, as well as assessment of the global trade and manufacturing policies that drive a majority of competitive differences. The data and tools developed can inform new policies that support U.S. manufacturers, and help industry prioritize key investments in manufacturing R&D and capital expenditures that can improve domestic manufacturing competitiveness [7, 8].

The results of the competitive analysis discussed here can be used to improve the cost structure of U.S. manufacturers and foster innovative manufacturing technology. Industry-led consortia, such as the Institutes for Manufacturing Innovation (established through the White House's National Network for Manufacturing Innovation), could serve as valuable forums to exchange knowledge, facilitate innovation, and develop technologies across industries and institutions that do not otherwise collaborate.

To advance domestic manufacturing competitiveness, the most promising new manufacturing technologies need to be scaled up and commercialized. Deploying new manufacturing technologies requires access to capital, which can be a significant barrier to U.S. manufacturers, especially the small and medium-sized businesses that make up a significant portion of the domestic wind supply chain. Analysis tools are needed to inform effective financial policies that enable domestic manufacturers to match and exceed the capabilities and capacity of foreign competition and manufacture the quantity, quality, and physical scale of next-generation wind plant technology [9].

Much of the cost of manufacturing is embedded in the raw materials and sub-assemblies that serve as inputs to the top tier manufacturers. Opportunities exist in steel mills, foundries, and fiber-reinforced polymer composite material suppliers to produce new standardized material forms that can reduce costly, high-labor content processes like welding or hand layup of composites that put domestic manufacturers at an inherent disadvantage due to the higher cost of labor in the United States. Coordinating with synergistic industries like aerospace, automotive, and offshore oil and gas would incent material suppliers with a diverse and sufficient market to retool or expand capacity. Best practices for wind turbine and wind plant decommissioning should also be developed in cooperation with the international wind industry to address the large amount of materials including steel and composites that will need to be recycled or dealt with in other ways as more plants reach the end of operation.

With respect to distributed wind, U.S. manufacturers dominate the domestic market for small wind turbines (i.e., through 100 kilowatts in size) and regularly export a noteworthy number of turbines [10]. In order for these manufacturers to remain competitive in the global market, continued investment in U.S. distributed wind turbine manufacturing technology and supply chain R&D is needed.

Successful implementation of these actions is expected to lead to an increasingly competitive domestic supply chain capable of achieving the deployment and cost goals of the *Wind Vision Study Scenario* and maximizing economic value for the nation. A competitive domestic manufacturing industry will also help develop and commercialize the many technologies described in Section 4.2, *Wind Plant Technology Advancement*. In addition to serving the domestic market, a sustainable U.S. supply chain could serve as a regional source for nearby emerging markets in the Americas and beyond, where an increasing share of the potential future global wind growth may take place [11].

Action 3.2: Develop Transportation, Construction, and Installation Solutions

Transporting, constructing, and installing the advanced technology described in the *Wind Vision* will present many challenges. Identifying these challenges and developing and implementing solutions to enable deployment of larger wind turbines on taller towers in new regions of the country and offshore will require strong cooperation between industry and government agencies.

As components grow in size and weight, the limitations of ground transport from factory to installation site increase, especially for land-based systems [12]. Issues include safety, the integrity of the public infrastructure, and increased cost of components designed around transportation constraints rather than performance optimization. Industry and state and local government agencies will need to assess the primary issues and write best practices to support improved logistics planning and clarify the transportation constraints. This will enable original equipment manufacturers and transportation and logistics companies to develop new component designs and logistics solutions to ensure larger turbines can be deployed cost-effectively. The use of larger turbines on taller towers is also affected by Federal Aviation Administration rules, which require additional review for structures over 500 feet. Actions to address these issues are discussed in Section 4.6, *Wind Siting and Permitting*.

ACTION 3.2: Develop Transportation, Construction, and Installation Solutions

Develop transportation, construction, and installation solutions for deployment of next-generation, larger wind turbines.

DELIVERABLE	IMPACT
Transportation, construction, and installation technology and methods capable of deploying next-generation land-based and offshore wind.	Reduced installed capital costs and deployment of cost-effective wind technology in more regions of the country.

Key Themes: Reduce Wind Costs; Expand Developable Areas
Markets Addressed: Land, Offshore

New construction and installation techniques, materials, and equipment, such as multi-crane lifts of heavy nacelles or concrete towers, will also be needed to install next-generation wind plant technologies. Concepts such as on-site manufacturing and assembly of towers or other components could mitigate some of the challenges presented by larger, heavier components, but will need to be demonstrated before being widely deployed. Dedicated technology demonstration sites could provide a venue to certify new construction and installation technologies without creating risk or otherwise affecting the financing of commercial projects. Once proven, these solutions could then be deployed on a broader scale.

Offshore wind is subject to unique challenges and will require new supply chain investments, including infrastructure and logistics networks. These issues are more thoroughly addressed in Action 3.3.

Action 3.3: Develop Offshore Wind Manufacturing and Supply Chain

Advancement of the U.S. offshore sector toward deployment—with initial projects readying for construction and lease sales establishing a flow of projects—brings into sharper focus issues related to manufacturing capacity, skilled workforce, and maritime infrastructure requirements. Studies commissioned by DOE and released in 2013–2014 provide a knowledge base for considering strategic approaches to planning, promoting, and investing in necessary industrial-scale wind assets in a cost-effective, efficient manner. These studies address port readiness [13][4]; manufacturing, supply chain, and workforce [14]; and vessel needs [15], each under a variety of deployment assumptions through 2030.

ACTION 3.3: Develop Offshore Wind Manufacturing and Supply Chain	
Establish a domestic offshore manufacturing, supply chain, and port infrastructure.	
DELIVERABLE	**IMPACT**
Increased domestic supply of offshore wind components and labor.	Increased economic growth in major offshore ports and regional manufacturing centers.
Key Themes: Increase Economic Value for the Nation **Markets Addressed:** Offshore	

Taken together, these assessments illustrate several principles:

- There is a wide range of economic development and job creation opportunities associated with offshore wind development. The United States has significant existing assets currently at the service of other industries or underutilized that can be deployed in support of offshore wind development.
- While offshore and land-based wind development share some commonalities, the offshore sector—due to larger component size, maritime logistics, rapidly advancing technology, and its early development phase—will require new skills and infrastructure development, and offers new and different economic development opportunities and challenges.
- Industrial infrastructure is primarily a function of market demand. The project-by-project approach of supply chain mobilization that is necessary for the first offshore wind projects will not be an effective or efficient process in planning for industry-scale deployment.
- The scale of deployment needed to support significant private sector investment in new manufacturing facilities, port improvement, and purpose-built vessel construction will likely be associated with regional markets for offshore wind and policies of multiple states.
- Development of the manufacturing base, workforce, and maritime infrastructure necessary to support a viable offshore wind industry will require integrated public and private sector vision, commitment, and investment.

European experience illustrates the significant effect on project cost and risk management that can result from supply chain gaps and vessel shortages [16, 17], and the dangers of losing economic development advantage in the competitive global offshore wind market due to a lack of strategic investment and planning [18]. Supply chain efficiencies have been targeted in the United Kingdom as a key opportunity for lowering the cost of offshore wind power [17]. The United States can capitalize on the lessons from Europe's experience to position the nation to realize offshore wind power's full economic development potential across participating states.

4. In addition to the port readiness report, DNV-GL created a port readiness tool (*http://www.offshorewindportreadiness.com*).

4.4 Wind Power Performance, Reliability, and Safety

Wind power is becoming a mainstream, widespread technology. With this progress, asset owner/operators, utilities, and the public expect wind plants to meet the same operational reliability as conventional generation sources. While substantial progress has been made in reliability and availability of systems, significant reductions in overall cost of energy can still be realized through better O&M practices. This is especially true in the offshore environment, where maintenance costs are significantly higher due to more difficult access. **These practices can be accomplished by the activities described in this section:**

- **Improve reliability and increase service life through the development of new technology and better understanding of operational environments;**
- **Develop a world-class database on wind plant operation under normal operating conditions;**
- **Develop understanding of reliability under severe operating conditions;**
- **Develop and document best practices in O&M procedures;**
- **Develop aftermarket technology upgrades and best practices for repowering and decommissioning**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.4.

Action 4.1: Improve Reliability and Increase Service Life

Reliability and a long economic service life are essential requirements for all power generation systems, and these attributes will become increasingly important for wind power systems as they supply greater portions of U.S. electricity demand. Unplanned replacement of wind turbine components is a major cost to wind plant owners and operators, both in terms of the cost to replace the components and in lost revenue from machine downtime.

ACTION 4.1: Improve Reliability and Increase Service Life	
Increase reliability by reducing unplanned maintenance through better design and testing of components, and through the adoption of condition monitoring systems and maintenance.	
DELIVERABLE	**IMPACT**
Reduced uncertainty in component reliability, and increased economic and service lifetimes.	Lower operational costs and financing rates. Increased energy capture and investment return.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore	

Improving wind turbine component, sub-system, and system reliability can reduce costs for O&M and component replacement, reduce downtime, and potentially reduce wind plant financing costs. Increasing the economic service life of wind power systems from the present 20–24 year design life to 25–35 years can further and significantly reduce the cost of these long-term energy production assets [19].

Strategies to improve reliability and service lifetime can target all phases of the wind power life cycle, including design, testing, manufacturing, operations, maintenance, refurbishment and upgrades, and recycling. Changing the design and certification philosophy at the design phase of product development to include a specific reliability basis will be an essential step. This includes planning for refurbishment, replacement, and product improvement upgrades early in the product development process.

Data from both field and controlled reliability testing are required to inform improved design practices and design standards. Collection and analysis of field data improve the understanding of environments and actual operating conditions in which each component operates and the specific mechanisms that cause early failure. Of particular importance is better understanding of the complex loads imposed in the interior of a wind plant. These data can be supplied by activities discussed in Section 4.1, *Wind Power Resources and Site Characterization*.

In addition to field tests, more comprehensive testing of components and subsystems will inform improved in-service reliability. Interactions between subsystems are a common source of reliability issues—for example, the interaction between a blade pitch bearing and the rotor hub that supports it, which is not perfectly rigid. Accelerated lifecycle testing of critical components under controlled conditions can be used to simulate operating environments. Present blade testing requirements can be augmented to also address testing of the drivetrain, electric power conversion system, and other key subsystems such as the blade pitch control system.

Beyond design for reliability and testing to identify failure modes and validate improved designs, condition monitoring systems can ensure that maintenance actions occur before failures occur. While industry is beginning to transition from traditional time-based component replacement schemes to condition-based component maintenance and replacement, and condition monitoring system sensors are becoming less costly, significant effort is still required to develop predictive analysis methodologies that convert the raw sensor data into actionable maintenance alerts.

Stakeholders can work together to conduct these activities through a cycle of robust design practices, testing and data collection, and targeted research projects, all informing the improvement of reliability standards and design testing.

Action 4.2: Develop a World-Class Database on Wind Plant Operation Under Normal Operating Conditions

Performance and reliability data from wind plants across the country are essential to understanding the state of the current fleet and benchmarking technology improvements. A trusted database will allow research funds to be directed towards the best opportunities to reduce cost of energy while also reducing uncertainty for financiers and insurance providers. Design standards will be improved by better understanding of the operating environment, and wind plant O&M practices will be optimized based on these data. Realizing this database will require cooperation among industry and research institutions such that maintenance records and turbine controller data can be collected from original equipment manufacturers, owner/operators, and third party service providers, in both warranty and out-of-warranty periods.

ACTION 4.2: Develop a World-Class Database on Wind Plant Operation under Normal Operating Conditions

Collect wind turbine performance and reliability data from wind plants to improve energy production and reliability under normal operating conditions.

DELIVERABLE	IMPACT
Database of wind turbine performance and reliability data representing the U.S. fleet.	Lower unplanned maintenance costs, lower financing and insurance rates, and increased energy production.

Key Themes: Reduce Wind Costs
Markets Addressed: Land, Offshore, Distributed

Action 4.3: Ensure Reliable Operation in Severe Operating Environments

As wind power installations increased in the United States, manufacturers encountered severe operating conditions such as lightning and erosion, especially in the western plains. With more wind plants being developed in colder climates and offshore installations pending, improvements are needed in turbine design to mitigate the effects of icing, salt water corrosion, and hurricanes. Despite these obstacles, reliable operation needs to be achieved to give financiers and regulators confidence in wind technology. This will require substantial work in data collection and model development, ultimately leading to the improvement of existing standards as well as possible creation of new ones. Research institutions need to collaborate with turbine manufacturers to perform targeted studies of each of these issues. The knowledge gained will facilitate structural and material design improvements to turbine components by the original equipment manufacturers, targeted mitigation solutions from third-party suppliers, and improved O&M practices from service companies.

ACTION 4.3: Ensure Reliable Operation in Severe Operating Environments	
Collect data, develop testing methods, and improve standards to ensure reliability under severe operating conditions including cold weather climates and areas prone to high force winds.	
DELIVERABLE	**IMPACT**
High availability and low component failure rates in all operating environments.	Lower unplanned maintenance costs, lower financing and insurance rates, and increased energy production.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore, Distributed	

Action 4.4: Develop and Document Best Practices in Wind O&M

Development of industry best practices is critical to the training and education of the workforce, the safety and efficiency of the work performed, and the energy production of the wind plant.

ACTION 4.4: Develop and Document Best Practices in Wind O&M	
Develop and promote best practices in O&M strategies and procedures for safe, optimized operations at wind plants.	
DELIVERABLE	**IMPACT**
Regular updates to the American Wind Energy Association's O&M Recommended Practices document and other industry-wide documents.	Consistency and improvement of O&M practices and transferability of worker skills.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore	

While the American Wind Energy Association's O&M Recommended Practices document [20] is a step in this direction, further improvement is needed to achieve the same level of standardization as conventional power sources. Progress in this activity will require the cooperation of trade organizations, government agencies, and wind industry members over the coming decades, and will necessitate extensive data collection. The result is expected to facilitate improved wind plant energy production, while minimizing integration and environmental impacts and increasing worker safety.

Action 4.5: Develop Aftermarket Technology Upgrades and Best Practices for Repowering and Decommissioning

The market in upgrades from both original equipment manufacturers and third-party suppliers is thriving. Owners of existing wind turbines—which are expected to remain in operation for 20 years or more—will want access to increased energy production, improved reliability, and decreased costs offered by improved technology as it is introduced into the market on new turbines. Rather than choosing more costly complete replacement of existing turbines, industry can continue to devise options for upgrades or refurbishment with replacement components offering the new technology. Specific actions include developing trusted remanufacturing and reconditioning techniques for expensive components; developing improved control systems and using technology from new turbines to accompany retrofits through better operational environment monitoring; and developing component retrofit and upgrade pathways such as larger or better performing rotors and more reliable drivetrains.

Wind turbine owners must decide what to do when wind turbines reach the end of their planned operating life. Options include repowering or refurbishing existing equipment or decommissioning the turbines.

ACTION 4.5: Develop Aftermarket Technology Upgrades and Best Practices for Repowering and Decommissioning	
Develop aftermarket upgrades to existing wind plants and establish a body of knowledge and research on best practices for wind plant repowering and decommissioning.	
DELIVERABLE	**IMPACT**
Aftermarket hardware and software upgrades to improve operational reliability and energy capture, along with reports and analyses on wind repowering and decommissioning.	Increased energy production and improved decision-making for aging wind plant assets, including repowering to avoid greenfield development costs.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land	

Establishing a body of knowledge, best practices, and strategy on wind repowering and wind plant retirements and decommissioning can help owners make cost-effective decisions. Creating such a body of knowledge requires research, data gathering, and review of existing practices.

Related actions that can be undertaken by wind stakeholders include:

- Analyzing and building on California and European experiences and practices in wind plant repowering and decommissioning of the earliest installed wind plants;
- Documenting repowering and decommissioning practices in other energy, transportation, and aerospace technologies;
- Developing and refining broadly accepted standards for recertification and life extension of wind plants and components; and
- Distilling best practices for wind plant decommissioning.

Success in this activity will require close collaboration between the wind plant owners and operators who will provide operational experience and the market for upgrades; original equipment manufacturers; and third-party equipment manufacturers who supply equipment for this market. Stakeholders also need to work together to find solutions for aging turbines that satisfy community concerns such as viewscape, land usage, and other environmental aspects, as well as the economic concerns of equipment and land owners.

4.5 Wind Electricity Delivery and Integration

Successfully addressing power system integration issues, while still maintaining electric power system reliability, is critical to achieving high wind penetrations at reasonable costs. Key issues in this area relate to increased variability and uncertainty posed by wind power at various time scales. Methods for managing the power system with moderate-to-high wind penetrations have evolved, and will likely continue to evolve as more actual experience is gained with wind power plants. Utilization of wind forecasting in operational practice of power systems and advanced controls on wind turbines can help operators decide on appropriate reserve levels. In some cases, operators will be able to deploy wind turbine and wind plant response capabilities to help manage the power system. Experience and research demonstrate these approaches can be executed at reasonable cost if appropriate actions are taken. If integration techniques are not appropriate, however, operating costs of the power system could be too high and wind deployment impeded.

Aggregate power system generation needs to match aggregate power system load instantaneously and continuously. Load, renewable generation such as wind and solar, and conventional generation all contribute variability and uncertainty.

Operating the power system with high penetrations of wind power while maintaining reliability at minimum cost requires actions in at least six key areas:

- **Encourage sufficient transmission to deliver potentially remote generation to load and provide for economically efficient[5] operation of the bulk power system over broad geographic and electrical regions;**
- **Encourage the availability of sufficient operational flexibility;**
- **Inform the design of proper incentives for investment in and deployment of the needed flexible resources[6];**
- **Provide advanced controls for grid integration;**
- **Develop optimized offshore wind grid architecture and integration strategies; and**
- **Improve distributed wind grid integration.**

Transmission network design to accommodate large amounts of wind power, which may be developed in remote locations including the Great Plains and the U.S. Continental Shelf, presents challenges. Linking large electrical and geographic areas, however, can help promote reliability and cost-effective bulk system operation [21]. Benefit and cost analyses of new transmission designs are needed to determine whether a given design is promising, and whether AC-only or AC-DC hybrid options make sense. The latter can tie asynchronous AC systems together and deliver wind energy and reliability benefits over large areas.

At high wind power penetrations, maintaining system balance while minimizing wind power curtailment requires that non-wind generators can be operated flexibly. This means generators may need to be ramped (changing output levels) and start/stop more quickly than was done without wind. Many older generators were not designed for the level of flexible operation that would likely be required by the *Wind Vision Study Scenario*. The supply of flexible resources, including demand response and storage as well as flexible conventional generation, needs to be increased to accommodate high levels of wind power. When cost effective, new storage technologies can be considered in the future.

The current electricity industry structure comprises regulated markets. The precise form of these markets varies, from regulated monopolies in much of the West and Southeast to regional transmission operator/independent system operator markets in much of the East, Texas, and California. A prerequisite to ensure that sufficient operational flexibility is available in real-time is an accurate assessment of future flexibility needs, along with market incentives to develop this level of flexibility. It is thus necessary to develop and implement operating practices and market structures that result in cost-effective power system operation, while maintaining reliability of delivery with high levels of wind power. These operating practices and market structures will inform the design of incentives to develop and deploy flexible resources as they are needed. As one example, specifications for new natural gas-fired capacity could require substantial operational flexibility.

Developing transmission, flexible generation, and market incentives are functions of the power system industry, including utilities, regional transmission operators, the regulatory community, and other entities involved in delivery of electricity. Market incentives are primarily market structures and designs that encourage flexibility and are part of the bulk power system. When these incentives are not in place, there can be a decline in flexibility. An example is the decline in frequency response in the Eastern Interconnection, caused in large part by a lack of market incentive [22, 23]. There is an important role for stakeholders in helping to develop best practices in power system operation and design, as well as in designing both physical and institutional systems to support achieving the *Wind Vision*. It will be critical to disseminate that information to power system operators and to support implementation of best practices.

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.5.

5. "Economically efficient" denotes the most cost-effective way of achieving the goal of operating the power system reliably with a given level of wind power. An outcome is economically inefficient if it provides the same level of reliability at higher cost.

6. For the purposes of this discussion, the term "resources" includes flexible generation, potential demand response, and appropriate storage.

Table 4–2. Texas Installed Wind Capacity and ERCOT Curtailment during CREZ Transmission Consideration, Approval, and Construction (2007–2013)

	2007	2008	2009	2010	2011	2012	2013
Texas installed wind capacity (MW)	4,446	7,118	9,410	10,089	10,394	12,214	12,354
Curtailment in ERCOT (fraction of potential wind generation)	1.2%	8.4%	17.1%	7.7%	8.5%	3.8%	1.2%

Note: The CREZ transmission project was approved by the Public Utility Commission in 2008. Construction was completed in 2013. The great majority of Texas' wind capacity is located in the ERCOT region (89% at the end of 2013).

Source: DOE 2008–2014 [25, 26, 27, 28, 29, 30, 31]

Action 5.1: Encourage Sufficient Transmission

Transmission is required to move wind energy from wind-rich regions to load centers. Balancing over large areas also requires transmission and can reduce operating cost. Studies are necessary to develop alternative transmission network designs that balance a range of technical, economic, and regulatory issues. While transmission expansion slowed for many years in the United States, the Electric Reliability Council of Texas's (ERCOT's) development of the Competitive Renewable Energy Zone (CREZ) transmission build-out demonstrates that the issue can be addressed. The CREZ project was enabled by the Texas Legislature in 2005 and Public Utility Commission action in 2008. Now complete, the 3,588 miles of Competitive Renewable Energy Zone transmission lines carry approximately 18,500 MW of wind power from West Texas and the Texas Panhandle to load centers in Austin, Dallas-Fort Worth, and San Antonio [24]. The CREZ line additions have substantially reduced wind curtailment in the ERCOT region, as discussed in Chapter 2 and summarized in Table 4-2.

ACTION 5.1: Encourage Sufficient Transmission	
Collaborate with the electric power sector to encourage sufficient transmission to deliver potentially remote generation to electricity consumers and provide for economically efficient operation of the bulk power system over broad geographic and electrical regions.	
DELIVERABLE	**IMPACT**
Studies, methodologies, and validated tools that inform cost-effective, reliable electricity delivery from wind power and all other generation types.	Increased transmission, reduced electricity costs, and increased wind generation with less curtailment.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore	

Other regions are following Texas's lead in adopting practices to enable long-needed grid upgrades that will benefit consumers while also reducing wind curtailment and enabling new wind development. The Midcontinent Independent System Operator has adopted similar broad cost allocation practices for a set of transmission lines, called the Multi-Value Projects, which will potentially integrate nearly 15 GW of new wind capacity. The Southwest Power Pool has similarly adopted a highway/byway transmission cost allocation policy and is making progress towards building a set of wind-serving lines called the Priority Projects. PJM Interconnection's State Agreement Approach allows projects with public policy benefits to be constructed when states agree to fund them, similar to the Texas CREZ.[7] In addition, PJM members

7. PJM Interconnection is a Regional Transmission Organization within the Eastern Interconnection. See *http://www.pjm.com/about-pjm.aspx* for more information.

have approved a new category of transmission projects called Multi-Driver Projects. These projects, which are subject to approval by the Federal Energy Regulatory Commission, would allow transmission upgrades with multiple benefits to proceed where they otherwise might not. Some other regions of the country have initiated coordinated planning activities but still lack the transmission cost allocation and planning practices essential for enabling multi-state transmission investment.

Transmission expansion is difficult but vital, because it spans issues ranging from detailed technical stability analysis to broad concerns about regulatory cost allocation. Complexity is further increased by the fact that transmission inherently connects large geographic areas. This raises the number of stakeholders and regulatory jurisdictions, creating the potential for multiple interveners in the approval process. Transmission projects also have very long lifecycles, which enhances their economic benefits but increases uncertainty in the value analysis. Transmission will not only help to effectively integrate wind power, but also increase bulk system reliability and reduce operating costs for the existing power system. This can provide benefits for the electricity ratepayer, but it complicates both the analysis and regulatory treatment of transmission expansion. For further discussion of transmission benefits analysis, see (for example) Chang et al, 2013 [32].

Transmission investment is also "lumpy," meaning that it is typically not cost-effective to build low-voltage lines at lower cost that may need upgrading in the lifetime of those lines (often 50 or more years). This implies greater levels of uncertainty surrounding the useful life of transmission and can suggest that transmission investments be made to accommodate distant-future needs and cover broad geographic regions. This may imply the need and opportunity for wind stakeholders to collaborate with others to inform large-scale, inter-regional, long-term planning to capture the economic benefits.

Several long distance DC transmission lines were under consideration as of 2014. Benefits of adding these lines include delivering remote wind and solar generation to load centers, improved reliability, reduced regulation and spinning reserve requirements, increased generator availability, and optimized generation dispatch benefits that capture diversity throughout the footprint.

To achieve a transmission infrastructure of the type that would support the *Wind Vision Study Scenario*, complex rules regarding transmission build-out over multiple jurisdictions will need to be addressed. The *Wind Vision* analysis finds the new transmission requirement in the *Wind Vision Central Study Scenario* is 2.7 times greater than in the *Baseline Scenario* by 2030, and 4.2 times greater by 2050 (see Chapter 3 for more detail).

There is evidence that initiatives such as the Texas CREZ can achieve this objective on an intra-state and intra-jurisdictional basis. While potentially achievable, however, transmission that crosses state boundaries may be difficult on such a large scale because local concerns may not align with broader social benefit.

Other issues that need to be addressed include determining whether system dynamics and system inertia[8] will be affected by large penetrations of wind power, and, if so, what cost-effective mitigation approaches can be used. Methods to analyze these impacts are not mature, and therefore need to be developed and refined. Once new methods and tools are developed, they need to be tested and then applied to expected high wind power penetrations at specific locations on the bulk power system to determine the potential impacts and mitigation strategies, if needed. There are new and emerging advanced control technologies that may be helpful, and these also need to be more fully developed and tested.

Action 5.2: Increase Flexible Resource Supply

Wind generation increases both the variability and uncertainty of the aggregate power system and, through displacement, reduces the amount of conventional generation that is under system operator control and available to balance net load. Sub-hourly energy markets and larger balancing areas reduce balancing requirements, but increasing the resource pool from which to balance is still necessary to cost-effectively integrate wind power. More flexible

8, System inertia is a measure of the ability of the system to ride through short-term disturbances by drawing on the mechanical "flywheel" inertia of spinning power plant rotors.

resources,[9] along with more flexible operating practice in the power system industry, are needed to integrate large amounts of wind power. Simply increasing the supply of flexible resources is a necessary, but not sufficient, condition to achieve flexibility in power system operations. In order for flexibility targets to be achieved, operating and market rules must not hinder access to the physical flexibility in the ground. Otherwise, physical flexibility can be stranded and thus unavailable to the power system operator.

ACTION 5.2: Increase Flexible Resource Supply	
Collaborate with the electric power sector to promote increased flexibility from all resources including conventional generation, demand response, wind and solar generation, and storage.	
DELIVERABLE	**IMPACT**
Analysis of flexibility requirements and capabilities of various resources. Frequent assessments of supply curve for flexibility. Implementation of cost-effective rules and technologies.	Reduced wind integration costs, reduced wind curtailment, improved power system efficiency and reliability.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

Because of the complexity of the power system and the uncertainty surrounding specific locations of new generation and transmission, analysis activities can help quantify the value of flexible resources. These resources include (but may not be limited to) reciprocating engine-driven generators, advanced aeroderivative combustion turbines, flexible combined cycle generators, demand response, purpose-built storage (e.g., pumped hydroelectric storage or large batteries) and inherent storage (e.g., domestic water heaters or plug-in automobiles with charge-discharge capability). Expanding the functionality of demand response and inherent storage provides opportunities for stakeholder action, including:

- Developing a more comprehensive assessment of these resources, including industrial loads;
- Reducing the cost of implementing demand response through development of appropriate monitoring and control technologies;
- Expanding the range of services provided by demand response, including frequency response, voltage support, and congestion relief;
- Analyzing the effect of new, innovative market designs, such as the influence of performance-based rates for frequency regulation per Federal Energy Regulatory Commission Orders 755 and 784, the impact of intra-hour scheduling requirements per Federal Energy Regulatory Commission Order 764, and the role of scarcity pricing and the intersection with capacity markets; and
- Coordinating wind with hydropower and solar to complement natural gas ramping to expand flexible resource supply and demand response capabilities.

There has been significant progress in developing flexible generation. For example, reciprocating engine plants can start within 60 seconds and fully load in 5 minutes, providing value for regions with high wind and solar penetration. There is no limit to the number of starts for these units, and no cycling cost. Coupled with simple cycle heat rates of approximately 8,800 BTU per kilowatt-hour (42% efficiency), plants such as these provide both flexibility and efficiency. A challenge remains in assuring that flexibility is correctly valued with appropriate reliability rules, operating practices, and bulk power system market design incentives.

Opportunities for stakeholder engagement and other collaborative efforts go beyond analysis of benefits and development of optimal utilization strategies. Technology-neutral reliability rules, operating practices, and market incentives can prescribe the required physical characteristics for flexible resources. This technical neutrality fosters competition between technologies and allows for advancements that may result in new sources of flexibility unforeseen at the time of rule development. One prerequisite in achieving a flexible power system is the creation of incentives that foster the development of needed resources.

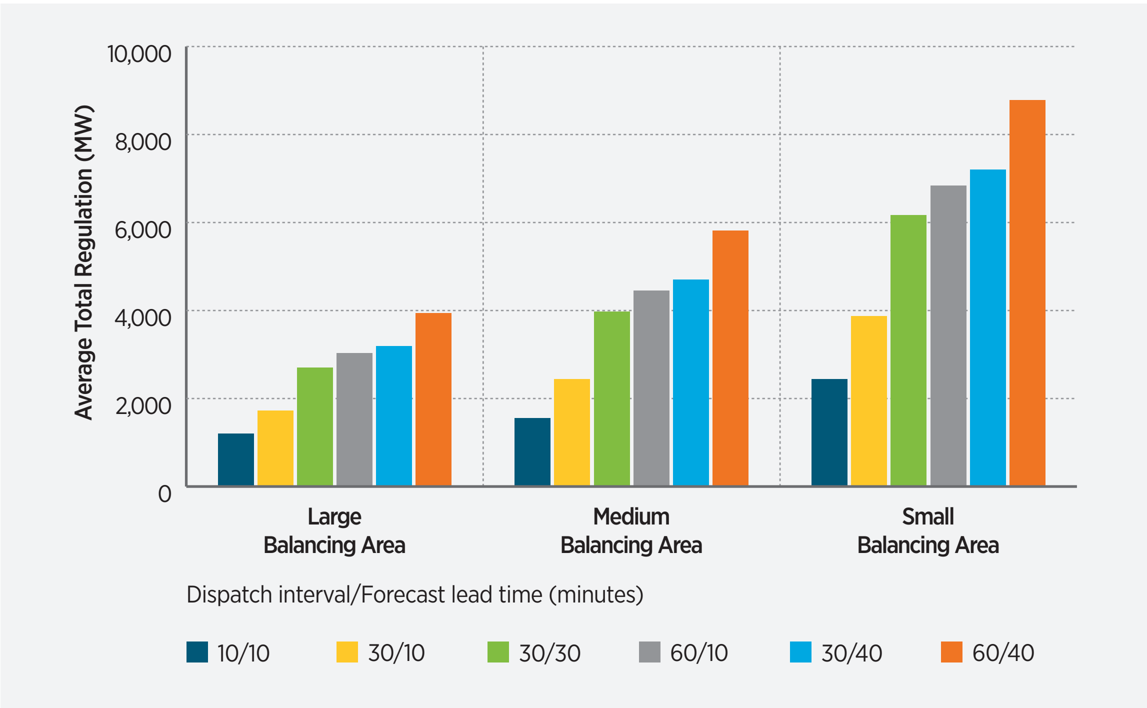
9. Flexibility of resources, which can be either generation or flexible demand or storage, is generally defined as the ability to change states quickly. Thus fast ramping and short start-up, shut-down, and up-/down-times are measures of flexibility.

Action 5.3: Encourage Cost-Effective Power System Operation with High Wind Penetration

Increasing industry understanding of wind integration and developing appropriate operating practices and technology-neutral market rules are necessary to further realize how to economically maintain power system reliability while accommodating increasing amounts of wind generation.

It is also necessary to inform power system operators which practices work and which do not by disseminating findings via publications, workshops, and conferences. This activity provides the scientific background necessary to help promulgate operating best practices, such as sub-hourly energy scheduling and balancing over larger areas, which have the potential to significantly reduce wind integration costs. This activity also illustrates the need for more flexible resources such as fast-starting conventional generation and increased demand response, which can also substantially reduce wind integration costs.

ACTION 5.3: Encourage Cost-Effective Power System Operation with High Wind Penetration	
Collaborate with the electric power sector to encourage operating practices and market structures that increase cost-effectiveness of power system operation with high levels of wind power.	
DELIVERABLE	**IMPACT**
Coordination of wind integration studies at the state and federal levels and promulgation of practical findings, especially to entities with less wind integration experience.	Increased wind integration levels, appropriate amounts of operating reserves, reduced curtailment, lower integration costs.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore	



Note: Increased balancing area size and faster scheduling reduce regulation requirements, and therefore reduce power system operating costs.
Source: Milligan et al. 2011 [33]

Figure 4–1. Increased balancing area size and faster scheduling reduce regulation requirements.

Larger balancing areas and faster generation dispatch (sub-hourly energy markets) considerably reduce wind integration costs. Figure 4-1 demonstrates that requirements for regulation—a relatively expensive balancing service—are reduced substantially as balancing area size is increased and the dispatch interval is decreased. For example, the regulation requirement for a large balancing area drops from 4,000 MW to just over 1,000 MW as the dispatch timeframe drops from 60 minutes to 10 minutes, and the forecast lead time is reduced from 40 minutes to 10 minutes. Analysis may be required to quantify benefits in regions that are not already implementing sub-hourly energy scheduling or that operate with small balancing areas. Implementation of best practices should also be supported.

The electric sector, with the assistance of DOE, its national laboratories, and federal and state regulators, support development of advanced techniques to reduce wind integration costs as well as studies that quantify the effects of potential regulatory and market structures. Such techniques and studies should seek to accurately encompass multiple balancing areas and regions as well as help promulgate best practices, such as optimization of flexibility reserve. These advanced methods can be used to address technology neutrality concerns, assuring that all technologies are treated equally in reliability rules and market structures.

Action 5.4: Provide Advanced Controls for Grid Integration

The bulk power system needs several ancillary services to help provide reliability and balancing capability. Wind turbines are being developed that can help with voltage control, regulation (automatic generation control), synthetic inertial response, and frequency regulation. Some of these features are untested, and, in many parts of the United States, wind turbine owners and operators have no incentive to provide these services because no market mechanism exists to pay the owners for providing these added capabilities. There is also a need to provide controls at the wind plant level, which would allow wind plants to behave more like conventional generation. The wind stakeholder community can collaborate with others to develop needed control strategies at the wind plant level, building upon newly emerging turbine capabilities.

ACTION 5.4: Provide Advanced Controls for Grid Integration	
Optimize wind power plant equipment and control strategies to facilitate integration into the electric power system, and provide balancing services such as regulation and voltage control.	
DELIVERABLE	**IMPACT**
Advanced wind turbine and wind plant controls that can be used to provide voltage support, regulation, synthetic inertial response, and frequency regulation by wind plants. Bulk power market designs and/or tariffs are necessary to pay for these services.	Allows power system operator access to additional flexibility from wind plants, when it is economical or necessary for reliability. This will reduce cost and increase reliability.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land; Offshore	

Action 5.5: Develop Optimized Offshore Wind Grid Architecture and Integration Strategies

In most cases, offshore wind power plants will be constructed in waters near large urban load centers. The *Wind Vision Study Scenario* includes the construction and integration of multiple offshore wind plants. Each project is individually responsible for the interconnection that brings power to shore. These power delivery systems will be built on public waterways and connected to the on-shore grid infrastructure. Under this activity, aggregating the power export systems for multiple offshore facilities is expected to lower the cost of offshore transmission and minimize impacts to coastal ecosystems where cables are routed. Several strategies are under consideration in the United States to develop optimized architectures for the orderly construction of an offshore grid. As part of this effort, close coordination between state and federal agencies is needed to streamline the offshore permitting process and reduce regulatory uncertainty.

ACTION 5.5: Develop Optimized Offshore Wind Grid Architecture and Integration Strategies	
Develop optimized subsea grid delivery systems and evaluate the integration of offshore wind under multiple arrangements to increase utility confidence in offshore wind.	
DELIVERABLE	**IMPACT**
Modeling tools and design information for utilities to evaluate infrastructure needs for offshore power delivery into land-based grid.	Increased utility confidence in offshore wind and reduced cost of offshore wind due to aggregation of power, lower environmental footprint, reduced transmission congestion, and possible higher capacity value.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Offshore	

Offshore wind electricity will typically be injected into heavily congested urban centers. As such, the integration of offshore wind in certain markets will have global utility effects that reduce the market price of electricity, at least for the near term. The capacity value of offshore wind differs from that of land-based wind and, in some regions, provides stronger matching with load during peak summer months. Both of these effects significantly influence the economics of offshore wind technology for the *Wind Vision Study Scenario*.

Action 5.6: Improve Distributed Wind Grid Integration

While utilities generally have experience integrating wind into the grid as well as confidence in land-based wind systems to deliver reliable power, distributed wind faces challenges in gaining a similar level of confidence and integration experience. The grid effects of distributed wind generation, alone and integrated with other forms of distributed generation, need to be better understood in order to facilitate mitigation and removal of integration barriers and to accelerate deployment. Better distribution system modeling tools, informed utilities, and standards development can reduce costs and increase confidence in distributed wind integration. This will improve prospects for increased distributed wind deployment. As an example, a new revision of IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems [34] is underway as of 2014. This revision will establish a framework for distributed generation that supports the grid and allows high levels of penetration.

ACTION 5.6: Improve Distributed Wind Grid Integration	
Improve grid integration of and increase utility confidence in distributed wind systems.	
DELIVERABLE	**IMPACT**
Modeling tools and information that utilities can use to evaluate integration of distributed wind into distribution systems.	Improved distributed wind power integration and delivery into distribution systems and increased utility confidence in this integration.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Distributed	

4.6 Wind Siting and Permitting

As with any form of energy, there are impacts to the natural surroundings associated with wind power. Wind is a comparatively clean source of energy with many positive attributes, such as no emissions, no air or water pollution, and no use of water in the generation of electricity. If improperly sited, however, wind power facilities may present a number of socioeconomic, conflicting use, and environmental risks. Care needs to be taken in the siting of wind power facilities to ensure the potential for negative impacts from construction and operation is minimized to the greatest extent practicable. These risks, or even the perception of risk, may pose obstacles to wind deployment throughout the United States. Regulators and other energy-sector decision makers need to ensure that energy generation choices reflect the public interest. To address this need, actions in this section focus on the real or perceived undesirable impacts of wind power and the development of regulations and policies that support wind development while equitably minimizing its real and perceived impacts.

Some potential impacts of wind are well-known and can be reduced and mitigated through existing siting and permitting processes (see Chapter 2 for more details). Other potential issues demand more research, either because the actual impacts are not quantifiable or because particular impacts to ecosystems or species of concern are not well understood. In some cases, there is also limited practical experience upon which decision makers can draw, such as with offshore wind on U.S. coasts or in the Great Lakes, or because of new or developing regulatory frameworks. The cost-effectiveness of new impact reduction and mitigation methods should be taken into account to understand if these methods are viable within the highly competitive U.S. energy sector or even necessary from a practical standpoint, as zero-impact development is not possible. **Five overriding actions important to responsible expansion of wind deployment are discussed in this section. They are:**

- **Evaluate potential competing public use challenges related to wind plants such as radar, aviation, land use, residential impact, commercial fisheries, maritime shipping, and navigation;**
- **Develop and disseminate relevant information on siting and mitigation strategies for wildlife and other natural resource concerns;**
- **Continue to gather and disseminate accurate information to the public on local impacts of wind power deployment and operations;**
- **Collaborate to inform streamlined regulatory frameworks for wind development on public land, and do so with the understanding that flexibility is needed to manage variability of wind projects by location; and**
- **Develop commonly accepted siting frameworks and assessment tools that can be used to inform faster wind site pre-screening.**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.6.

Action 6.1: Develop Mitigation Options for Competing Human Use Concerns

Wind power plants often cover the same geographical area as other potential uses, bringing about discussions of conflicts. In most cases, wind technology can operate without impacting other uses, such as with most civil aviation. In some cases, however, such as with military and weather radar systems, the potential interactions need to be better understood and may be location- and use-specific. In cases such as navigation, military operations, and commercial and recreational fisheries, detailed discussions with potentially affected stakeholders are needed. Other potential impacts, such as those on local viewsheds or tourism, are often a matter of public perception. Addressing these may require engagement with a broader range of stakeholders. To effectively characterize the challenges and develop mitigation options for any of these issues, detailed discussions and—in many cases—experimental research will be required.

ACTION 6.1: Develop Mitigation Options for Competing Human Use Concerns	
Develop impact reduction and mitigation options for competing human use concerns such as radar, aviation, maritime shipping, and navigation.	
DELIVERABLE	**IMPACT**
A better understanding of the impacts of wind development and appropriate mitigation options leading to streamlined site assessment and trusted hardware and software technology solutions that address the most pressing competing use conflicts.	Decreased impact of all wind technologies allowing project developers to site wind projects while limiting competing public use impacts.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

A large number of key conflicting uses are already understood for land-based wind development. Competing uses for expanded offshore wind development are less defined, but aviation safety, navigation safety, radar, and competing economic uses are known to be of importance. One of the initial steps for ensuring thorough understanding of competing uses is the development of expanded geographic information tools in which multiple data sets related to land and water uses are collected from a broad group of public and private stakeholders. A common, vetted, and complete database will help facilitate discussions and planning between wind development and other human use concerns. For competing uses that are a matter of safety, security, or similar concerns, detailed understanding of the potential conflicts needs to be developed with participation of all concerned stakeholders. With this understanding, mitigation strategies (which may include new hardware and software technologies) can be developed, tested, and verified to reduce impacts and enable cost-effective wind deployment that meets stakeholder needs.

Action 6.2: Develop Strategies to Minimize and Mitigate Siting and Environmental Impacts

Potential impacts of wind deployment on wildlife and other ecological systems include the direct mortality of individual birds and bats; injury or behavioral impacts to marine life as a consequence of construction or operational noise in the offshore space; and fragmentation or disturbance of wildlife habitat. Although understanding already exists about these impacts, filling knowledge gaps will require nation-wide investment in species-specific, long-term research. Such research has historically fallen to individual project developers, resulting in a patchwork of sometimes inconsistent research that makes reaching a national consensus difficult.

ACTION 6.2: Develop Strategies to Minimize and Mitigate Siting and Environmental Impacts	
Develop and disseminate relevant information as well as minimization and mitigation strategies to reduce the environmental impacts of wind power plants, including impacts on wildlife.	
DELIVERABLE	**IMPACT**
Accurate information and peer-reviewed studies on actual environmental impacts of wind power deployment, including on wildlife and wildlife habitat.	Decreased environmental impact by all wind technologies, improved understanding of the relative impact of wind development, defined methodologies to assess potential impacts and risks, and shorter and less expensive project deployment timelines.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

Determining whether additional measures need to be employed and what those measures should be requires building from existing understanding of wind power's effects, balancing wind power's positive attributes with its potential negative impacts, and considering these impacts in comparison to other forms of energy generation. Potential mitigation options identified through this process should be developed, tested, evaluated for cost-effectiveness in comparison to the expected benefit, and put into practice as needed. Outreach to a broad range of stakeholders should also continue, to ensure interested parties understand the true and relative impacts of expanded wind deployment. This will permit contextual discussion on relative environmental impacts of wind specifically and the power sector in general, reducing the chance that disproportionately burdensome requirements will be implemented for wind. As turbine development moves into new areas and the effects of climate change become more pronounced, the impact of wind development and the status of specific species may change. Ongoing assessments and research will be required.

In order to understand the potential long-term impacts of expanded wind development and enhance coexistence of wind power and wildlife, large-scale wildlife and metocean baseline studies will be required. Existing avoidance and minimization options, such as bat deterrent technology and reduction of impacts through operational minimization measures (changes in turbine operations during high risk periods, such as fall migration) also need to be further assessed. This information will help determine effectiveness and appropriate application of these strategies along with other conservation support approaches, such as habitat preservation. The end goal is to provide the industry with multiple, cost-effective ways to reduce—and, to the extent practicable, fully offset—the expected impacts of specific wind projects.

Action 6.3: Develop Information and Strategies to Mitigate the Local Impact of Wind Deployment and Operation

Wind deployment can pose real or perceived public impacts to communities and individuals that live in close proximity to wind power facilities of all sizes. Although wind offers many positive attributes related to the environment (e.g., avoiding air and water pollution, reductions in water usage), as well as to jobs, local land payments, taxes, and other community benefits, there are also potential challenges such as visual or aesthetic impacts, annoyance associated with turbine noise, and physical safety issues such as ice-throw. Location-specific public opinion can be negatively affected due to misconceptions about these concerns or a lack of understanding of wider community benefits.

ACTION 6.3: Develop Information and Strategies to Mitigate the Local Impact of Wind Deployment and Operation	
Continue to develop and disseminate accurate information to the public on local impacts of wind power deployment and operations.	
DELIVERABLE	**IMPACT**
Accurate information and peer-reviewed studies on the impacts of wind power deployment that can be used and shared through a variety of platforms.	Decreased impact by all wind technologies, defined methodologies to assess potential impact, and shorter and less expensive project deployment timelines.
Key Themes: Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

As discussed in Chapter 2, substantial information already exists about many of these impacts. In some instances, however, more is still to be understood and documented about the specific impacts and benefits to communities as a result of wind power development. As wind turbines are deployed into new areas or locations in closer proximity to population centers, further research on public impacts will be needed to reduce or eliminate concerns for specific projects and to mitigate real community impacts in an appropriate and cost-effective manner. Stakeholders need to develop a better documented understanding of community concerns and expected benefits, foster accurate assessment tools, and identify appropriate mitigation strategies to address the largest impacts. Ongoing outreach by the wider stakeholder community is needed, so that communities that may be affected by a new wind power development can make decisions based on current, accurate, and widely accepted information.

Action 6.4: Develop Clear and Consistent Regulatory Guidelines for Wind Development

Wind projects trigger a number of regulatory requirements at federal, state, and local levels. The regulations and associated governing bodies that might affect any single wind project depend on a number of variables, including whether a project is on public or private land, the state and locality of the project, and its size. This variation in permitting processes and requirements across locations and government levels can cause inconsistencies in project timelines and increase project risk. In addition, uncertainty about future federal regulatory actions that might affect wind projects is causing hesitation in certain areas of the country, such as those with populations of bat species that may be listed as threatened or endangered in the near future. Effective mitigation measures can help counteract this uncertainty by providing industry with tools to address new regulations and meet permitting requirements.

ACTION 6.4: Develop Clear and Consistent Regulatory Guidelines for Wind Development	
Streamline regulatory guidelines for responsible project development on federal, state, and private lands, as well as in offshore areas.	
DELIVERABLE	**IMPACT**
Defined regulatory guidelines for the deployment of offshore, land-based, and distributed wind turbines, developed in collaboration with the wind industry to provide comprehensible and geographically consistent regulations for the deployment of wind technologies.	Allows developers to clearly understand the processes to deploy wind technologies on federal, state, or private lands, thus reducing costs.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

Concise regulatory guidelines are needed that are easy for developers to understand and that address stakeholder needs up front (to avoid conflicts mid-development), such as robust pre-application processes. Guidelines will vary across the country and between levels of government due to jurisdictional, social, and environmental differences. Consistency across agencies and levels of government in such features as the types of information needed to apply for permits, permitting timelines, and opportunities for direct coordination between developers and multiple agencies and levels of government could make permitting easier and more efficient and predictable for developers.

Action 6.5: Develop Wind Site Pre-Screening Tools

Existing requirements, processes, and frameworks for siting wind projects are often loosely coordinated or completely uncoordinated. Such tools range from those to inform site selection and permitting, including tools used to conduct noise or flicker assessments, to those used for initial site screening. Tools can be proprietary, fee-based, or publicly available, and none are housed in a central location or consistently used.

ACTION 6.5: Develop Wind Site Pre-Screening Tools	
Develop commonly accepted standard siting and risk assessment tools allowing rapid pre-screening of potential development sites.	
DELIVERABLE	**IMPACT**
A single or series of interlinked siting tools that support wind turbine siting.	Decreased permitting time while easing permitting processes, leading to lower project development costs with improved siting and public acceptance.
Key Themes: Reduce Wind Costs **Markets Addressed:** Land, Offshore, Distributed	

Despite the broad range of types and access models for siting tools, no commonly accepted guidelines or set of tool standards exists to ensure such tools are accurate or uniformly applied to inform siting decisions. As a result, organizations on opposing sides of a siting dialogue will often report varying results because they are using different models and assumptions to address similar questions. Additionally, there are no clearly defined screening approaches that allow federal or state regulators to quickly assess potential projects. This results in a more formal and lengthy assessment process, even for projects with limited potential conflicts. While it is impractical to develop universal pre-screening tools that will apply to every situation, there are benefits to providing common best practices where applicable and identifying opportunities to improve efficiencies among federal and state agencies for siting on public lands.

The creation of siting tools should be approached with the understanding that there is broad diversity in wind plant development and informational requirements that are typically based on local and regional concerns. Any guidelines for siting should also be considered conceptual in context. If those conditions are met, the creation of trusted siting tools and wind plant development guidelines can support local wind development while reducing costs through streamlined permitting and the minimization of additional regulatory requirements. These guidelines and accompanying software tool standards are expected to help ensure project assessment accuracy. These activities should help facilitate responsible wind plant development.

4.7 Collaboration, Education, and Outreach

Wind power development has experienced remarkable growth in terms of both deployment and technology innovation. The wind industry is seeing generational changes over the course of years, not decades, which can make it challenging for people not directly involved to stay abreast of this rapidly changing industry. Collaboration among domestic and international wind plant developers and operators, researchers, and other stakeholders during this time of rapid change facilitates learning about new approaches and technical advances that can lead to increased turbine performance, shorter deployment timelines, and lower overall costs.

Public perceptions and regulatory treatment of wind power generation are also influenced by public information that may be incorrect or misleading. Without active collaboration among interested parties, the education of policymakers at all levels, and outreach to stakeholders and the public in general, outdated perceptions of wind power will prevail, limiting the technology's potential and increasing overall project costs.

Given the rapidly evolving wind technology and deployment landscapes, achieving Wind Vision deployment levels will require:

- **Providing information on wind power impacts and benefits to increase public understanding of societal impacts; and**
- **Fostering international exchange and collaboration on technology R&D, standards and certifications, and best practices in deployment.**

Detailed activities and suggested timelines for action are identified for each of these key areas in Appendix M.7.

Action 7.1: Provide Information on Wind Power Impacts and Benefits

Decision makers and the public often lack thorough knowledge about the social costs and benefits of different electricity generation options. As such, decisions are sometimes made about electricity options based on perception, without clear understanding of the actual impacts of those options. These perceptions can influence project permitting and siting timelines, and—if negative—can potentially increase project costs. Accurate, objective, and accessible information about the actual impacts and benefits of wind power can help stakeholders make decisions about wind that are right for their communities.

Quantitative analysis and public dissemination efforts are needed from both public and private sectors of the wind community regarding the relevant positive and negative externalities, including economic outcomes. These efforts need to put potential risks of wind development in the context of the potential benefits, such as jobs, tax revenues for local communities, and avoided environmental impacts. Balanced information will improve decision making about wind development and ensure deployment takes place in an environmentally and socially responsible manner. To the extent possible, impact reduction and mitigation techniques for real impacts on a regional or location-specific basis also need to be articulated. Information should include unique considerations for offshore, land-based, and distributed wind developments.

ACTION 7.1: Provide Information on Wind Power Impacts and Benefits	
Increase public understanding of broader societal impacts of wind power, including economic outcomes; reduced emissions of carbon dioxide, other greenhouse gases, and chemical and particulate pollutants; less water use, and greater energy diversity.	
DELIVERABLE	**IMPACT**
Information and peer-reviewed studies delivered in a stakeholder-targeted method that provides accurate information on the impacts and benefits of wind power independently and in relation to other energy choices.	Retention or expansion of areas open to wind development; decreased fear and misconceptions about wind power; lower project deployment costs and timelines; all leading to more wind installations, better public relations, and lower costs of power.
Key Themes: Expand Developable Areas; Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

Action 7.2: Foster International Exchange and Collaboration

The wind industry has become a global trade. Although markets are dominated by Europe, Asia, and the United States, expanded potential exists worldwide. For the wind industry to remain vibrant, an international approach to market development and research collaboration should be considered. Expanding beyond development of wind turbine standards as discussed in Action 2.2, international exchange and collaboration will be required to provide market consistency for U.S. manufacturing and allow global experts to work collaboratively to address ongoing research questions.

International exchanges and expanded information sharing through multilateral organizations such as the International Energy Agency and the International Renewable Energy Agency provide three key benefits: 1) exchange of ideas, research methods, and results among private and public researchers and educational professionals; 2) expanded knowledge of the applicability of wind technology; and 3) experience addressing the deployment challenges of integration, public acceptance, environmental impact, and competing land use. The resulting expansion of wind deployment will allow for increased research and data that can lead to lower costs, and will open export markets for U.S. manufacturing. Along with continued domestic demand, this growing international market can help stabilize the U.S. wind industry and allow industry-wide efficiency improvements.

ACTION 7.2: Foster International Exchange and Collaboration	
Foster international exchange and collaboration on technology R&D, standards and certifications, and best practices in siting, operations, repowering, and decommissioning.	
DELIVERABLE	**IMPACT**
Expanded international collaboration including information sharing, joint research, and staff exchanges allowing expanded education about wind power and expert collaboration from across the wind industry.	Expanded understanding of benefits of wind power across the energy sector; expanded cross-industry collaboration on pressing research topics.
Key Themes: Reduce Wind Costs; Expand Developable Areas **Markets Addressed:** Land, Offshore, Distributed	

Specific actions for international collaboration include an increased number of cross-border research projects funded by various parties; extended collaboration on the development and use of testing infrastructure; and expanded researcher and academic exchanges—including, for example, permanent researcher-in-residence programs at national laboratories worldwide. Greater international collaboration on the development of wind power research agendas would also be useful.

4.8 Workforce Development

Realizing *Wind Vision Study Scenario* deployment levels and the associated benefits requires a robust and qualified workforce to support the industry throughout the product lifecycle. The industry needs a range of wind professionals, from specialized design engineers to installation and maintenance technicians, to enable the design, installation, operation, and maintenance of wind power systems. To support these needs, advanced planning and coordination are essential to educate a U.S. workforce from primary school through advanced degrees.

Programs at the primary school level introduce developing students to the role of renewable technologies and the range of skills needed to address market requirements. Programs at the secondary school level can add detail and context about wind and other renewable technologies, including practical applications and the scientific and mathematical elements required. Activities targeted at trade workers through community college and vocational technical certification processes supply the wind industry with the much needed technical workforce to install and maintain the expanded fleet of wind plants described in the *Wind Vision*. Finally, specialized skills are developed at the college and advanced degree levels to support wind turbine design, innovation, manufacturing, project development, siting and installation, and additional professional roles.

This section discusses development of comprehensive training, workforce, and educational programs designed to encourage and anticipate the technical and advanced-degree workforce needed by the industry.

Detailed activities and suggested timelines for action are identified for this key area in Appendix M.8.

Action 8.1: Develop Comprehensive Training, Workforce, and Educational Programs

Since wind is a relatively new entrant in domestic and international energy markets, the wind power educational and training infrastructure lags behind that of other major energy technologies. A degree in petroleum engineering is available at a wide range of academic institutions, but similar degrees in wind engineering are only available at a handful of schools. The absence of common understanding and defined credentials in the land-based, offshore, and distributed wind industries leads to on-the-job training, which increases safety risks for operational staff and leads to errors and inefficiencies. The development of a nationally coordinated educational system addressing all levels will require the collaboration of multiple U.S. federal and state agencies, industry, and the educational community.

ACTION 8.1: Develop Comprehensive Training, Workforce, and Educational Programs	
Develop comprehensive training, workforce, and educational programs, with engagement from primary schools through university degree programs, to encourage and anticipate the technical and advanced-degree workforce needed by the industry.	
DELIVERABLE	**IMPACT**
A highly skilled, national workforce guided by specific training standards and defined job credentials to support the growth of the wind industry.	Sustainable workforce to support the domestic and as appropriate the expanding international wind industry.
Key Themes: Reduce Wind Costs, Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

An estimated total of more than 50,000 onsite and supply chain jobs were supported by wind investments nationally as of the end of 2013 [35]. As detailed in Chapter 3, the central sensitivity case of the *Wind Vision* scenario is projected to support a robust domestic wind industry, with jobs from investments in new and operating wind plants ranging from 201,000 to 265,000 in 2020, and increasing to 526,000 to 670,000 in 2050. The *Wind Vision Central Study Scenario* relies on the Energy Information Administration's Annual Energy Outlook 2014 reference data [36] and other literature-derived model inputs and is intended to reflect the central estimate of future effects. The expected expansion of international wind development will greatly increase these needs, further taxing domestic staffing needs but allowing an excellent opportunity for U.S.-based academic institutions interested in renewable energy technology development.

Cross-governmental coordination can help federal and state institutions efficiently mobilize activities in the wind industry. Creating national wind training standards for community college and university sectors requires vision, momentum, and focus in advance of growing demands for skilled individuals; the development of educational programs is a long-term, time-intensive, and expensive process. This foresight will prepare resources to respond to evolving market demands. Stakeholder actions to support the development and implementation of a comprehensive, wind-focused training and educational program across the educational spectrum include:

- National activities allowing better coordination among all parties to implement a national education and training infrastructure for wind technologies;
- Activities targeting primary and secondary students to expand engagement in energy-related issues and the STEM (science, technology, engineering, and math) fields;
- Efforts to expand community college and vocational training programs and educational standards for all wind technology areas; and
- Consistent and prolonged endeavors to support wind-focused academic institutions and activities at the university and postgraduate levels to ensure a healthy population of wind power professionals with a wide range of expertise, including the sciences, engineering, law, and business.

Numerous efforts are underway to support and expand wind industry workforce development options and to better understand the wind industry's workforce development needs. Various industry groups and educational organizations have already implemented workforce development programs. Activities are also supported by DOE's Wind and Water Power Technologies Office, the American Wind Energy Association, the U.S. Department of Labor, and the National Science Foundation. Many of these efforts are uncoordinated, however, with few direct ties to defined levels of expertise. One of the first actions to support the *Wind Vision Study Scenario* is to improve understanding and coordination of the workforce and educational needs for the wind sector, particularly among academia and industry stakeholders.

The active engagement of students at the primary and secondary levels not only introduces more people to the impacts and benefits of wind power, but also "primes the pump" of the wind power workforce at all levels. Opportunities in STEM topics, including energy and wind technologies, should be made available to students at the K–12 level so they will have the skills and interest to possibly enter the renewable energy workforce. Jobs resulting from these areas of study may be technical, but opportunities exist in policy, regulation, communications, finance, and other support activities.

Because the majority of wind power jobs are supported by community college and vocational level education, a common core of industry-wide job accreditation standards and implementation programs at these levels and in technical centers is essential. Worker education and safety instruction are also critical. Safety certifications for land-based and offshore wind differ, so targeted education and safety guidance are necessary for both. The expanding wind market will require creation of a framework for wind O&M technicians, with particular focus relating to offshore wind development. In addition, clear pathways should be made available for short-service construction workers (land-based and offshore) and vessel operators (offshore) to obtain training and certification related to wind. The industry requires broader, facilitated collaboration to ensure universal understanding of the required skills and defined achievement levels. This understanding will help improve quality of the overall workforce as well as enhance worker flexibility and development. For distributed wind, continued expansion of the market requires more trained site assessors, installers, and maintenance providers.

Many of the skills required for the long-term success of the wind industry, from engineering to business, require individuals with advanced degrees. This need was discussed in a 2013 study by Leventhal and Tegen [37]. Specific actions required include the development of a sustainable university consortium to support R&D efforts; technical training and student collaboration; implementation of an international academic network; creation of sustainable wind-focused university programs; and expansion of opportunities for student, industry, and university collaborations such as internships, research fellowships, and joint research projects.

4.9 Policy Analysis

Wind power offers social benefits and plays a valuable role in the nation's diverse portfolio of electricity generation technologies, but also has potential impacts and faces competition from other electricity generation technologies. National, state, and local policy and regulatory decisions made today and into the future play a significant role in determining the growth of wind power.

Achieving wind power deployment to fulfill national energy, societal, and environmental goals—while minimizing the cost of meeting those goals—is likely to require practical and efficient policy mechanisms that support (directly or indirectly) all three wind power markets: land-based, offshore, and distributed. Objective and comprehensive evaluation of different policy mechanisms is therefore needed, as are comparative assessments of the costs, benefits and impacts of various energy technologies. Regular assessment of progress to enable ongoing prioritization of roadmap actions is also essential.

This section discusses three key areas in which the wind stakeholder community can collaborate with others to maintain the analysis capability necessary to inform policy decision makers:

- **Comprehensively evaluate the costs, benefits, and impacts of energy technologies;**
- **Refine and apply policy analysis methods; and**
- **Track technology advancement and deployment progress and update the roadmap.**

Action 9.1: Refine and Apply Energy Technology Cost and Benefit Evaluation Methods

Thorough evaluation of the costs, benefits, and impacts for all electricity generation alternatives is needed to help guide policy decisions and approaches to achieve societal goals. Historically, comparative evaluations have been based primarily on performance characteristics and direct costs. Various external factors that are not always reflected in direct costs—such as health, water, climate, economic development, and diversity impacts, as well as local impacts on ecosystems and humans—have often not been explored in detail.

ACTION 9.1: Refine and Apply Energy Technology Cost and Benefit Evaluation Methods	
Refine and apply methodologies to comprehensively evaluate and compare the costs, benefits, risks, uncertainties, and other impacts of energy technologies.	
DELIVERABLE	**IMPACT**
A set of recognized and approved methodologies to objectively evaluate the costs, benefits, and impacts of energy technologies, in concert with regular application of these tools.	Increased decision maker access to comprehensive, comparative energy information.
Key Themes: Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

Chapter 3 quantifies many of these cost and benefit impacts for wind using best available methods. Additional comprehensive methods are needed for quantifying the full spectrum of costs, benefits, and impacts for all generation options, as well as relative risks and their impacts. These methods would ideally consider various attributes and impacts, and would do so at different geographic and time scales. In some cases, methods to quantify specific impacts do not exist; in other cases, methods exist but are not comprehensively or consistently applied. Further challenge comes in comparing seemingly incommensurable impacts (e.g., comparing bird deaths from wind turbines to air pollution from fossil energy plants), or in determining the specific costs, benefits, and impacts that are appropriate to consider in any particular decision (e.g., carbon effects might be appropriate to consider in national policymaking, but may not be relevant in a local siting decision for a specific wind project). As such, there is a need and opportunity for stakeholder engagement and collaboration not only in methods development, but also in supporting the proper application of those methods by decision makers at the national, state, and local levels.

To become commonly used and accepted, tools will need to be unbiased, with input and buy-in from a wide array of stakeholders. Federal agencies, national laboratories, and academic institutions may be particularly well-positioned to meet this need for comprehensive and unbiased analysis.

Action 9.2: Refine and Apply Policy Analysis Methods

Ongoing reviews of energy and environmental policies are required to evaluate existing policies and enable course corrections as needed, as well as to assess the potential impacts of proposed policies to determine whether they will achieve desired outcomes. A key need and opportunity is to better understand the relative advantages and disadvantages of policy mechanisms that might be used to support renewable energy such as wind, as well as to achieve broader societal goals. The wind community needs to stay abreast of existing and proposed policy options at both the federal and state levels.

Several policies have been used to directly encourage wind power deployment: tax incentives at the federal level, renewable portfolio standards at the state level, and targeted incentive programs for distributed and offshore wind applications. Other types of policy mechanisms under consideration or already in limited use include federal renewable or clean energy portfolio standards, programs to reduce the cost of wind project financing, and policy mechanisms to control the release of greenhouse gas emissions.

Some of the data, models, and tools needed to provide objective energy and environmental policy analysis are already available, but further refinement is an ongoing need, particularly as new policy mechanisms are proposed. One specific need and stakeholder opportunity is to ensure that modeling tools used to evaluate policy options at the federal and state level are able to capture the unique geographic and operational characteristics of wind technology, as well as evolving technology advancements. This need exists for land-based, offshore, and distributed wind applications.

This need for more advanced tools extends beyond wind power and includes improved representation of individual energy technologies as well as electric system planning and operations. To date, energy policy has often been targeted at specific sectors, such as direct incentive support for renewable energy applications. There is broad recognition in the literature, however, that cost-effective achievement of certain societal goals—such as climate change mitigation and reduction in criteria air pollution emissions—calls for broader application of policies focused on external factors that are not always reflected in direct costs. Such policies might include economy-wide pricing of carbon emissions and environmental regulations that comprehensively limit criteria air pollution.

ACTION 9.2: Refine and Apply Policy Analysis Methods	
Refine and apply policy analysis methodologies to understand federal and state policy decisions affecting the electric sector portfolio.	
DELIVERABLE	**IMPACT**
A set of recognized and approved methodologies to objectively evaluate the economic, environmental, societal, and wind-industry impacts of existing and possible future energy policies, in concert with regular application of these tools.	Increased decision maker access to comprehensive evaluations of energy policy options to achieve wind power deployment in fulfillment of national energy, societal, and environmental goals, while minimizing the cost of meeting those goals.
Key Themes: Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

Wind stakeholders can collaborate with others, such as those in the broader energy and environmental sectors, to conduct objective analyses that explore the implications of energy policy development on society and the wind industry. A diverse group of entities will continue to create and apply policy analysis tools, both on a commercial basis and to serve specific stakeholder interests. Federal agencies, national laboratories, and academic institutions may be especially well positioned to meet the need for comprehensive and unbiased tools development and policy analysis.

Action 9.3: Maintain the Roadmap as a Vibrant, Active Process for Achieving the Wind Vision Study Scenario

The *Wind Vision* roadmap is intended to be a living document, continually updated to inform stakeholder engagement as technology evolves, deployment expands, and new challenges arise. Roadmap updates will be used as a means to track progress toward the *Wind Vision Study Scenario*. Stakeholders may revisit and revise the roadmap periodically so that it reflects changing circumstances while driving forward momentum.

ACTION 9.3: Maintain the Roadmap as a Vibrant, Active Process for Achieving the *Wind Vision Study Scenario*	
Track wind technology advancement and deployment progress, prioritize R&D activities, and regularly update the wind roadmap.	
DELIVERABLE	**IMPACT**
Periodically produced publicly available reports tracking technology advancement and deployment progress, as well as updated wind roadmaps.	Systematic evaluation of progress towards increased domestic deployment of wind power and identification of any new challenges to be addressed.
Key Themes: Reduce Wind Costs; Expand Developable Areas; Increase Economic Value for the Nation **Markets Addressed:** Land, Offshore, Distributed	

An abundance of information can be learned from existing wind installations over time, including performance trends, cost trends, O&M experience, technology developments, and electric system integration experience. Accurate tracking and reporting of this information for all three wind markets provides a valuable record of progress in wind technology and applications, as well as early indication of any issues that require attention. This record can inform deliberations and analysis of deployment, policies, and R&D priorities, as well as provide ongoing perspective on the status of wind deployment in the United States relative to the roadmap. As such, stakeholder effort in assembling a thorough and accurate record of U.S. experience with wind power—in all of its applications—is essential. The wind and electric power sectors will play a major role in providing the relevant data, though third-party entities may be best positioned to aggregate, organize, and publish the information while protecting confidentiality.

A range of options for improving cost effectiveness of wind technology and facilitating the technology's use and acceptance are under consideration in both the public and private sectors of the wind community. Stakeholders can support ongoing refinements to the methods used to evaluate and quantify the relative merits of these options, so that priority can be given to those with the greatest expected benefits for complete wind systems. Wind technology advancement opportunities need to be evaluated and tracked in the context of the entire wind power system (or even the entire electric power system) in order to systematically improve the technology's cost effectiveness. Publicly available reports are needed that explain R&D evaluation and prioritization methods as well as the potential influence of successful R&D efforts on the cost of wind technology. R&D priorities then need to be revisited periodically to account for progress made and changing conditions.

Wind industry involvement is required to produce the relevant data to track wind deployment in the United States and provide critical insight on R&D priorities and roadmap revisions. Stakeholders may consider engaging DOE, in conjunction with its national laboratories, as an unbiased third-party to track progress, evaluate technology advancement programs, and update the roadmap.

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