

Prospective Costs, Benefits, and Impacts of U.S. Renewable Portfolio Standards



- Overview and Project Background
- Modeling Framework and Electric Sector Results
- Electric Sector System Costs and Electricity Price Estimates
- Air Pollution Emissions
- Greenhouse Gas Emissions
- Water Use Reduction
- Gross Renewable Energy Workforce Requirements
- Natural Gas Price Reduction
- Summary and Conclusions

Project Goal, Coverage, Audience

- **Goal:** Evaluate the potential costs, benefits, and impacts of state RPS policies going forward, monetized where possible, based on a consistent analytical framework and set of tools: considering both an existing RPS scenario and an expanded RPS scenario
- **Intended Audiences:**
 - **State RPS administrators:** Provide a framework and methodology that states can build upon and refine for their own analyses; methods, assumptions, and caveats are all fully documented
 - **Broader audiences:** Communicate aspects of the value of state RPS programs and the scale of various potential costs, benefits, and impacts, to inform decision making
- **Previous Work:**
 - Wisser et al. (2016). A Retrospective Analysis of the Benefits and Impacts of U.S. Renewable Portfolio Standards.
 - Uses AVERT to estimate avoided generation and emissions
 - Applies range of methods to estimate benefits and impacts from incremental RE used to meet state RPS policies in 2013
 - Does not address costs or prospective impacts
 - Heeter et al. (2014) & Barbose et al. (2015): Cost and Benefits of State-Level RPS.
 - Survey approach using reported costs and various methods
 - Focuses primarily on recent retrospective annual costs

Project Support and Team

- Supported by DOE EERE Office of Strategic Programs
- Executed by a respected LBNL/NREL analysis team

Category	Researchers
Coordination	Galen Barbose, Lori Bird, Jenny Heeter, Trieu Mai, Ryan Wiser
ReEDS analysis	Trieu Mai, Venkat Krishnan
Air Pollution	Dev Millstein, Ryan Wiser
GHG	Ryan Wiser, Trieu Mai
Water	Jordan Macknick
Workforce requirements	David Keyser
Natural Gas	Trieu Mai

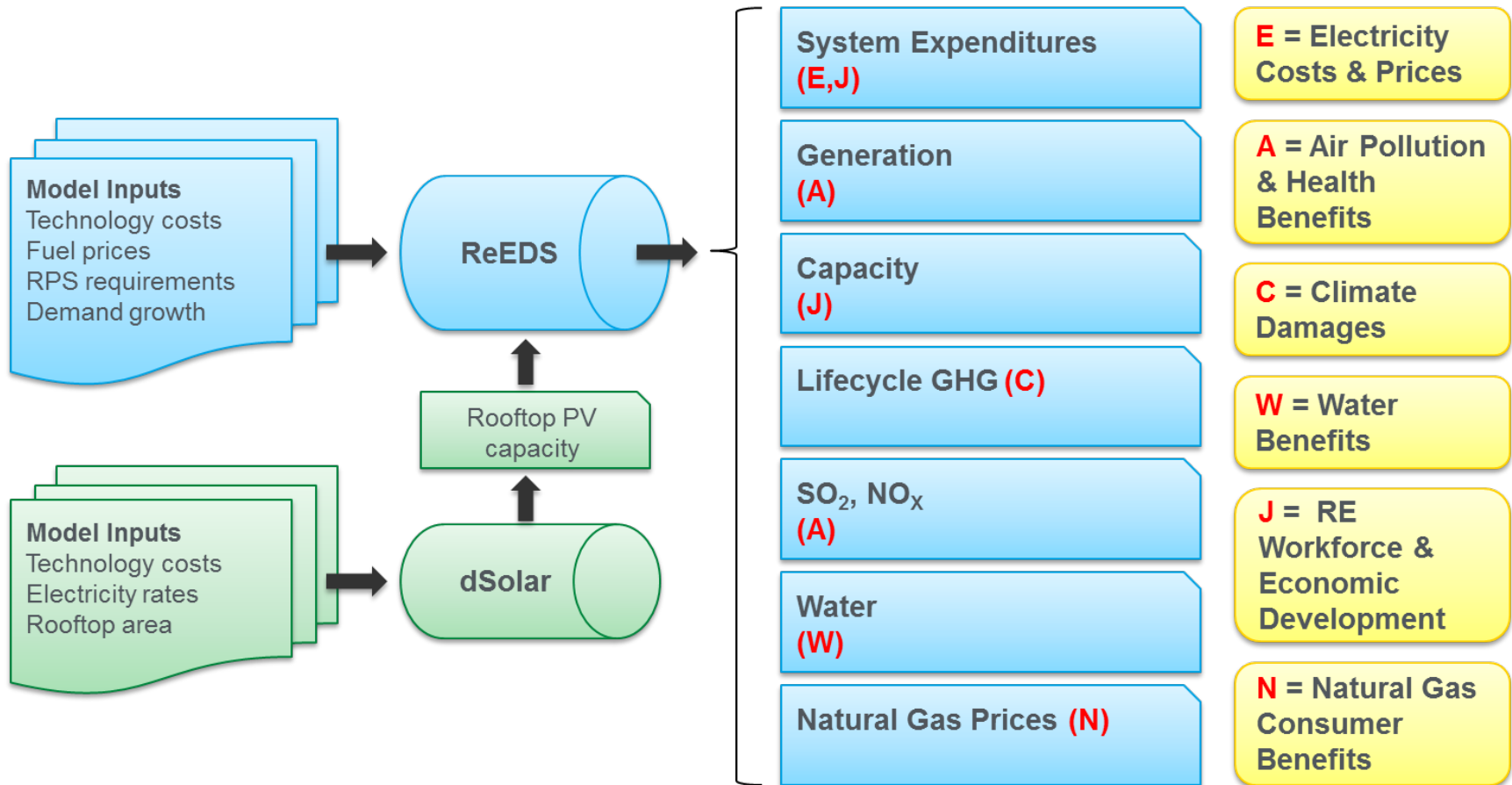
- **Benefits versus Impacts:** We distinguish between potential societal *benefits* (air pollution, GHG, water use reductions) and other *impacts* (gross jobs, natural gas prices)
- **Scope of Costs, Benefits, and Impacts:** We consider an important subset of—but not all—potential costs, benefits, and other impacts (e.g., land use, wildlife, and distribution-level integration are not considered)
- **Cost-effectiveness:** RPS programs are not the only possible way to achieve the outcomes discussed in this paper, and may not be the least-cost approach
- **Additionality:** We estimate the impacts *associated with RE used to meet* RPS demand growth, but do not seek to *attribute* those effects solely to RPS policies
- **Uncertainty:** Considerable uncertainty underlies many elements of our analysis

Modeling Framework and Electric Sector Results

Trieu Mai, Venkat Krishnan

Methodology

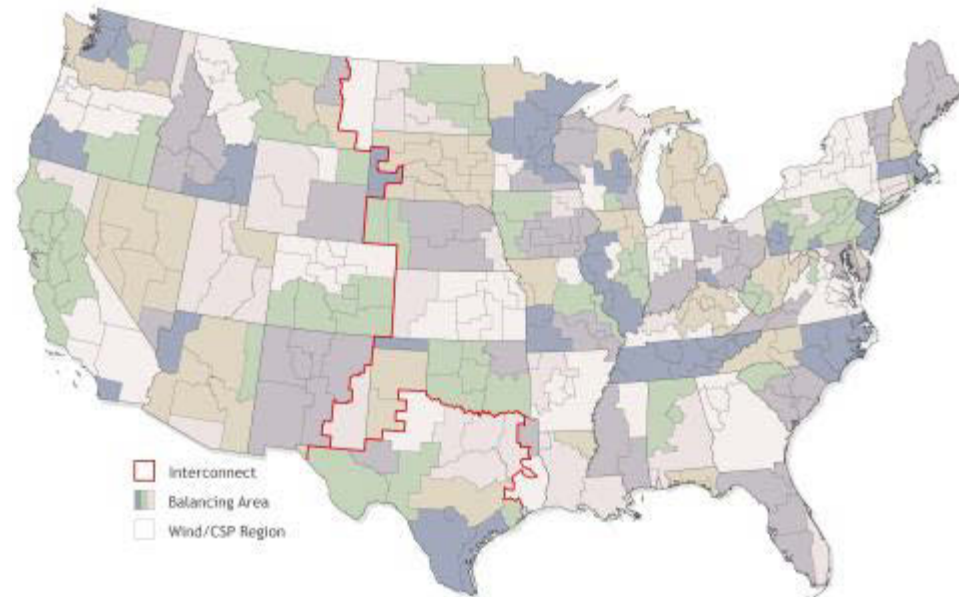
Methods closely follow other DOE-funded reports, using ReEDS and dSolar in concert with other analytical tools and computations to estimate costs, benefits, and impacts



Regional Energy Deployment System (ReEDS) model

ReEDS is a spatially and temporally resolved capacity expansion model that identifies optimal scenarios for the U.S. electric sector

- High spatial resolution to represent both transmission and spatial mismatch of resource and load
 - 134 Balancing Areas (BAs), 356 wind/CSP regions, 48 States
- High temporal resolution to represent seasonal and diurnal variations in load and resources
 - 17 time-slices for each year
- Statistical consideration of integration issues due to variability and uncertainty of RE supply
- Constraints designed to address: reliability, resource supply, transmission, national and state policies



<http://www.nrel.gov/analysis/reeds/>

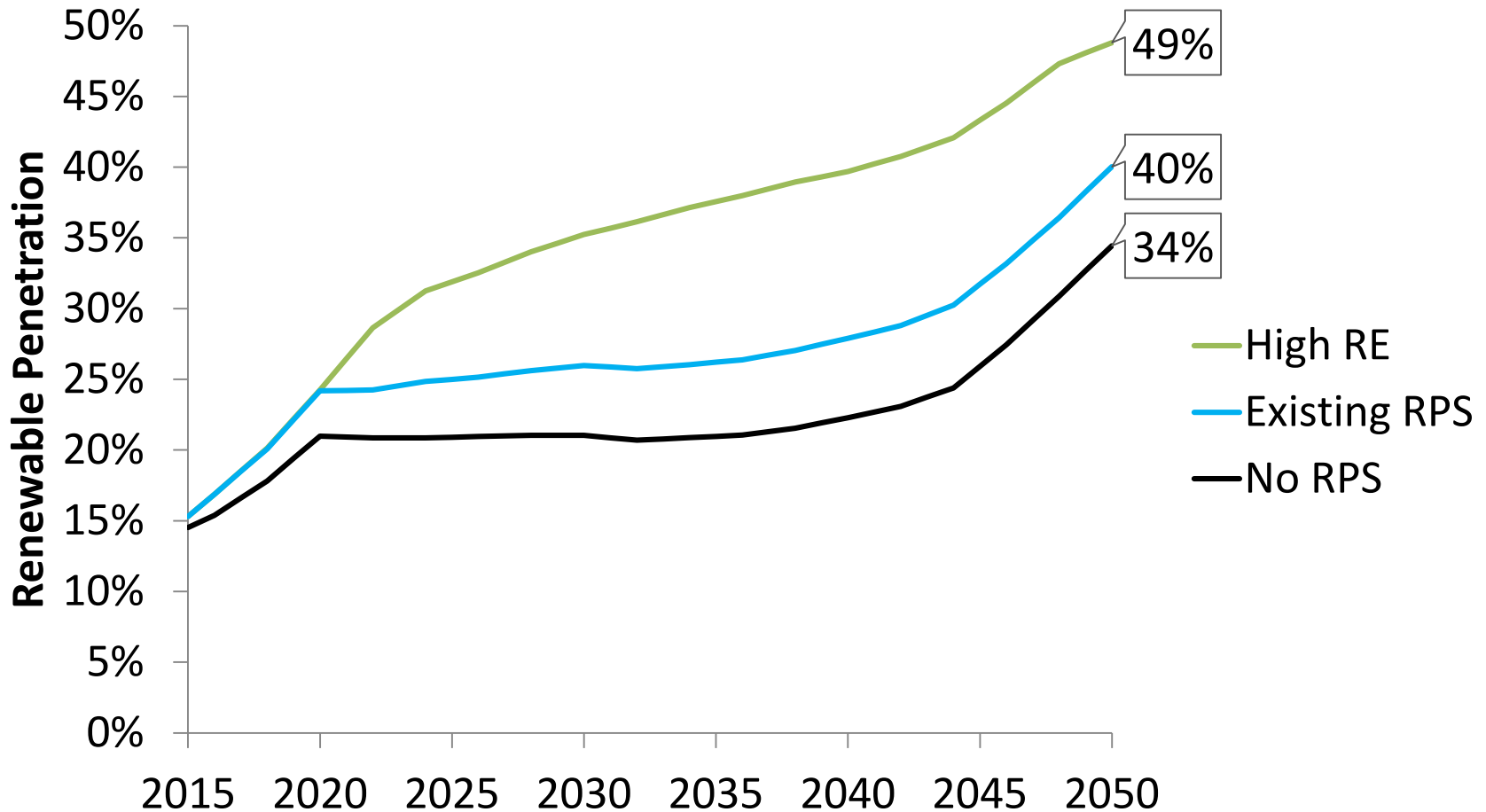
Scenarios and Sensitivities

Scenario Parameters	No RPS Scenario	Existing RPS Scenario	High RE Scenario
RPS treatment	No RPS after 2014	Includes recent RPS revisions - through early 2016	Includes recent RPS revisions - through early 2016
CPP treatment	No CPP	No CPP	CPP - mass-based targets with new source complements - no credit trading
Bounding assumptions	- Upper bound on RE generation based on “economic” RE from RPS scenario		- Upper bound on NG generation (at the state level) from the Existing RPS scenario - Reflects an RE-based compliance pathway for the CPP
DPV assumptions	DPV reduced by RPS DG carve-outs	DPV from Standard Scenarios	DPV from Standard Scenarios

- *Uses ReEDS v2016 Final Release version with RPS updates*
- *Key assumptions from AEO 2016 Reference case and ATB 2016 Mid case*
- *Additional sets of sensitivities modeled with low/high natural gas prices (based on AEO 2016 High/Low Oil & Gas cases) and low/high RE technology costs (based on ATB 2016 High/Low Cost cases) – these are used to inform estimated cost ranges only*
- *Results presented at the census division level to better capture the net impacts over a broader region as electricity imports/exports can be impacted by state policies*

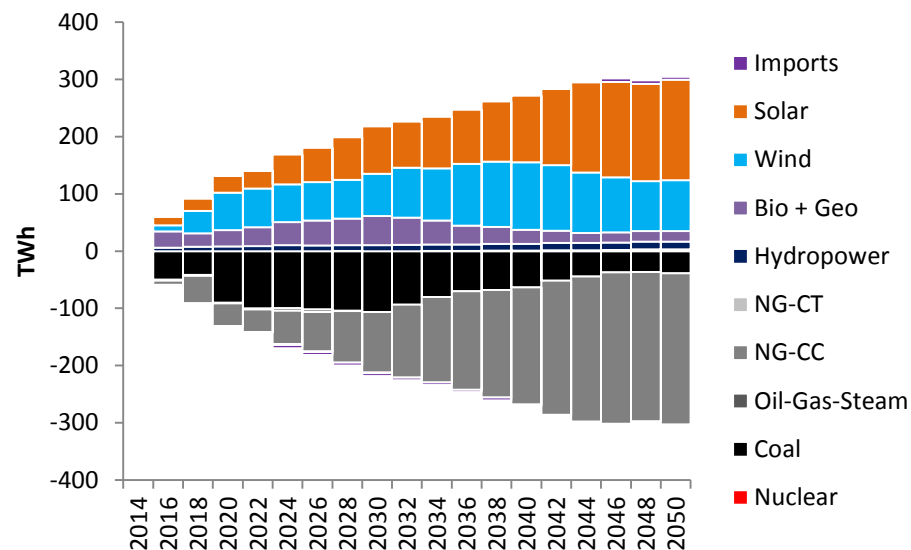
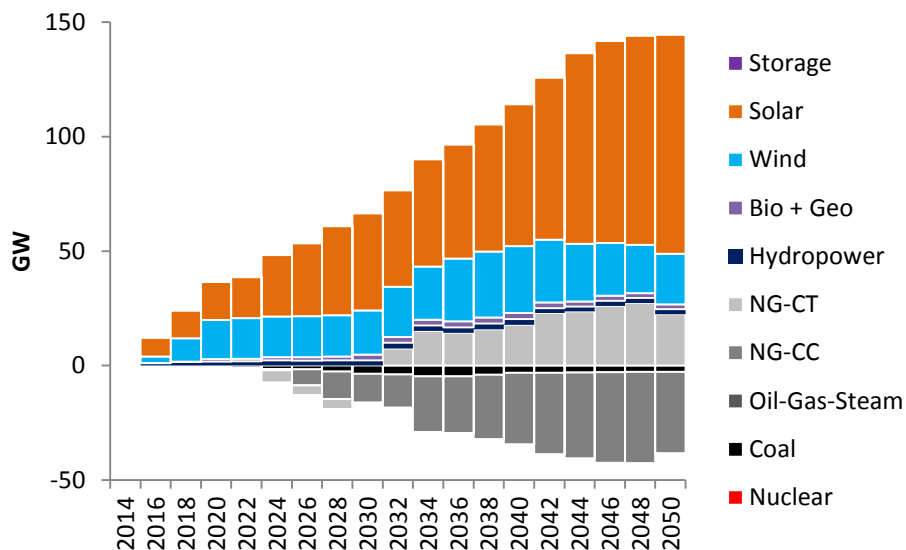
**Scenario design used to measure the impacts of RE used to meet
existing and expanded RPS policies**

U.S. Renewable Penetration Varies from 34% to 49% in 2050



2015 RE penetration was 14% with about half from hydropower generation

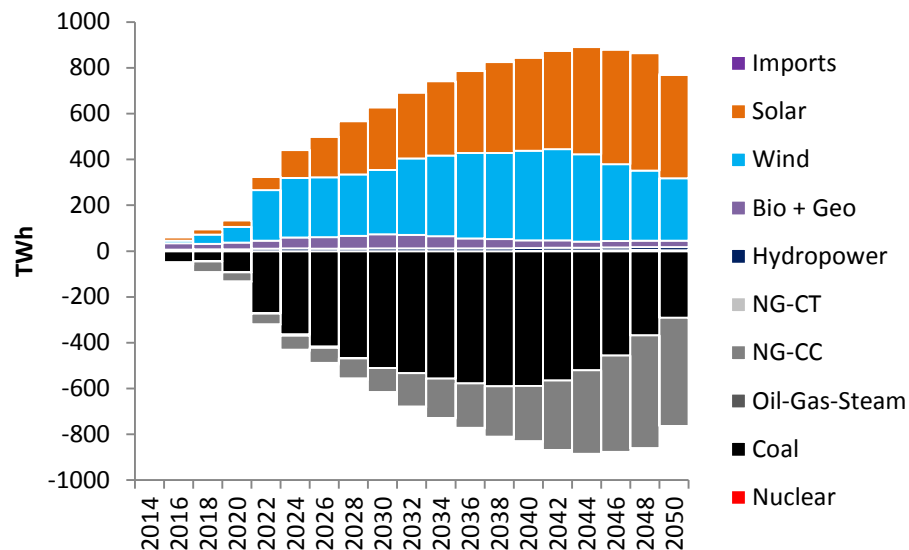
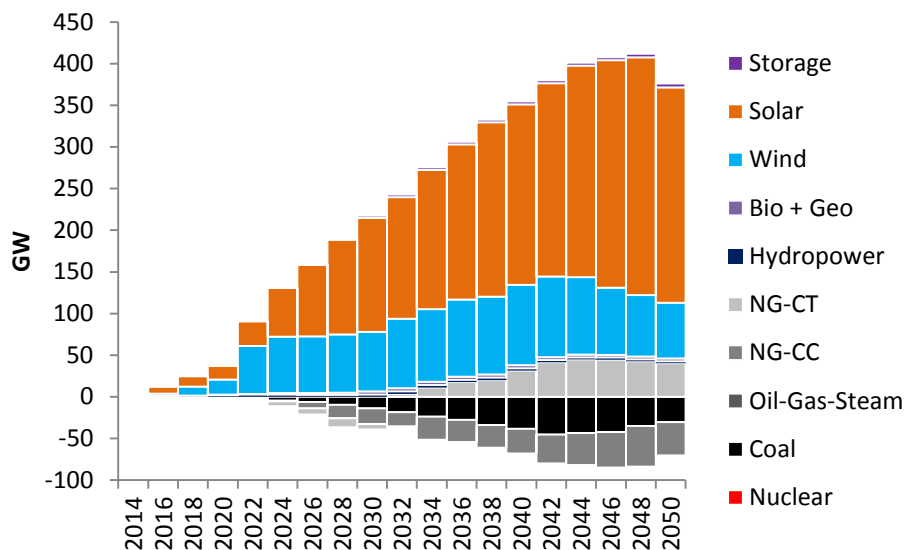
Existing RPSs Require 66 GW RE Above Non-RPS RE by 2030; 218 TWh



Note: distribution of incremental RE generation is sensitive to technology cost assumptions

- Most incremental capacity and generation split between wind and solar, but significant incremental generation from biomass and geothermal as well
- Incremental RE generation largely offsets fossil generation, with slightly greater coal offset before 2030, but larger share of natural gas offset in the longer term

High RE Scenario Requires 215 GW RE Above Non-RPS RE by 2030; 627 TWh

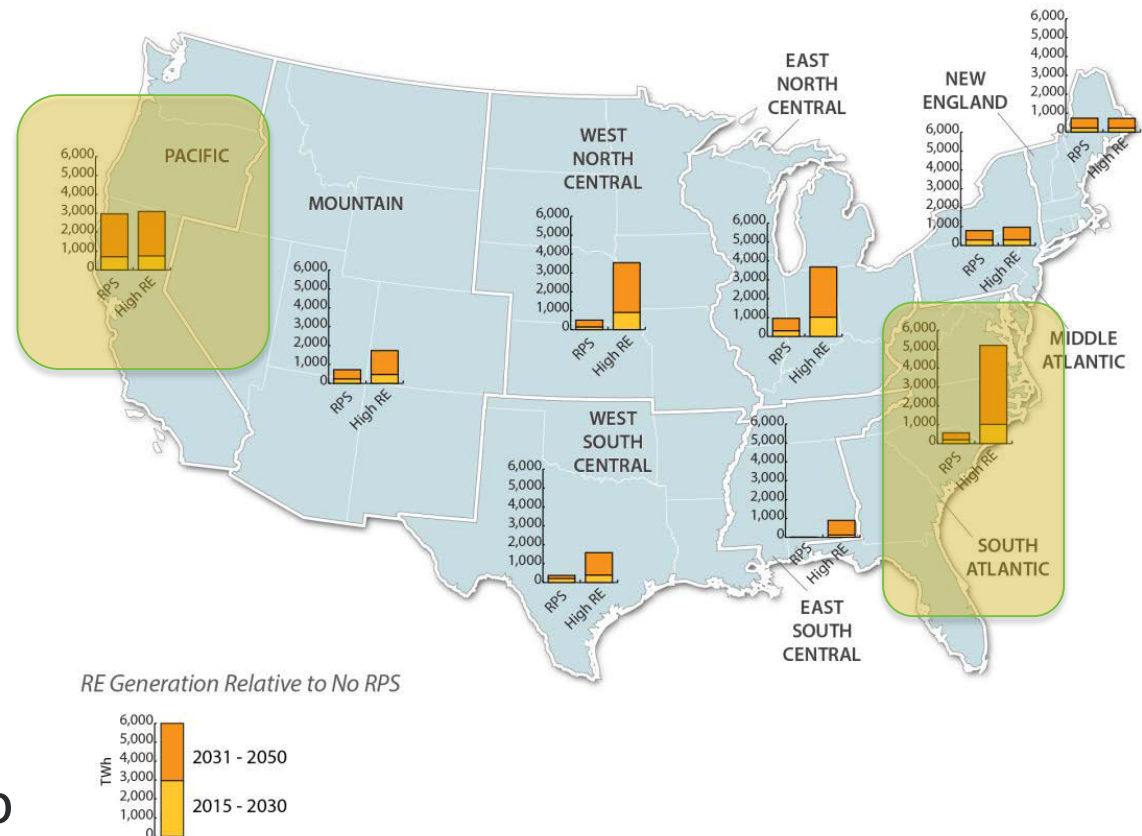


Note: distribution of incremental RE generation is sensitive to technology cost assumptions

- Nearly all incremental RE is from wind and solar generation
- Coal comprises the dominant avoided generation, even more so than in the Existing RPS scenario due, in part, to the location of RE deployment and the design of the scenario with a carbon emissions constraint
 - After 2030 greater amounts of coal capacity are estimated to retire in the High RE scenario and incremental NG-CT capacity is deployed offsetting the avoided NG-CC capacity

Regional Cumulative Incremental RE Generation

- Existing RPS drives greatest absolute amounts of incremental RE in Pacific region
- More uniform spatial distribution of incremental RE generation found in the High RE scenario



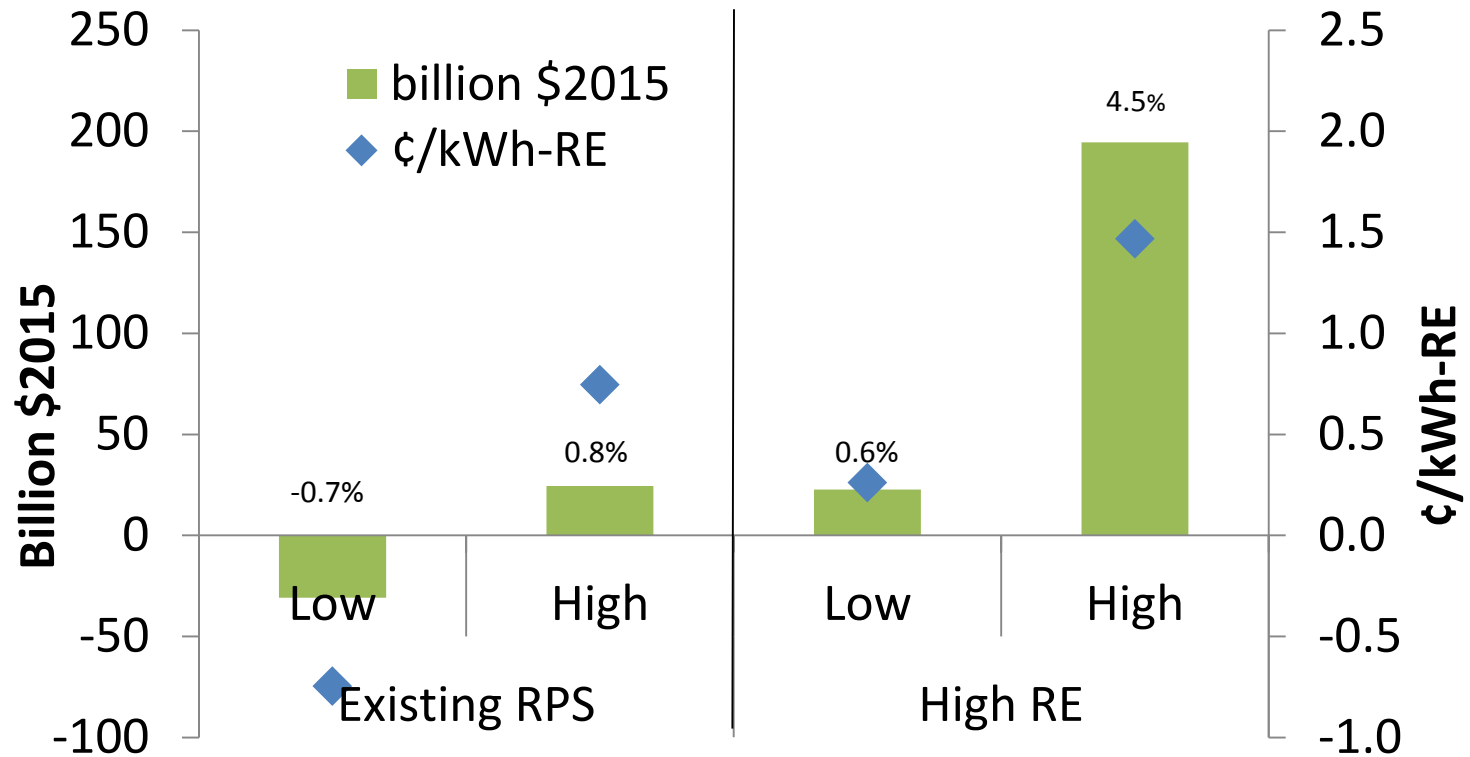
Electric Sector System Costs and Electricity Price Estimates

Trieu Mai, Venkat Krishnan

Cost Estimates: Considerations and Limitations

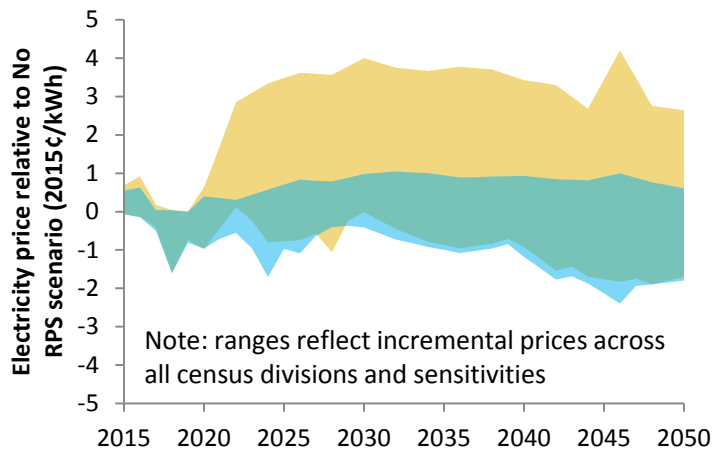
- Cost estimates include capital, O&M, and fuel costs for generation, storage, and transmission infrastructure and operations
 - Incremental system cost results exclude Federal tax incentives
 - Electricity price results include Federal tax incentives
- Uncertainty ranges are estimated based on ReEDS renewable technology cost and natural gas sensitivities; quantified ranges of other benefits and impacts are based on other underlying uncertainties
- **Key limitations and caveats:**
 - *System-wide optimization*: Investment and dispatch considers the contiguous U.S. as a whole; non-economic decisions are not considered
 - *Siting and supply chain*: ReEDS does not explicitly model siting and supply-chain constraints
 - *Foresight*: Only limited foresight is modeled in ReEDS

Present Value of Incremental System Costs Vary Depending on Scenario, Natural Gas Prices, and Renewable Technology Costs

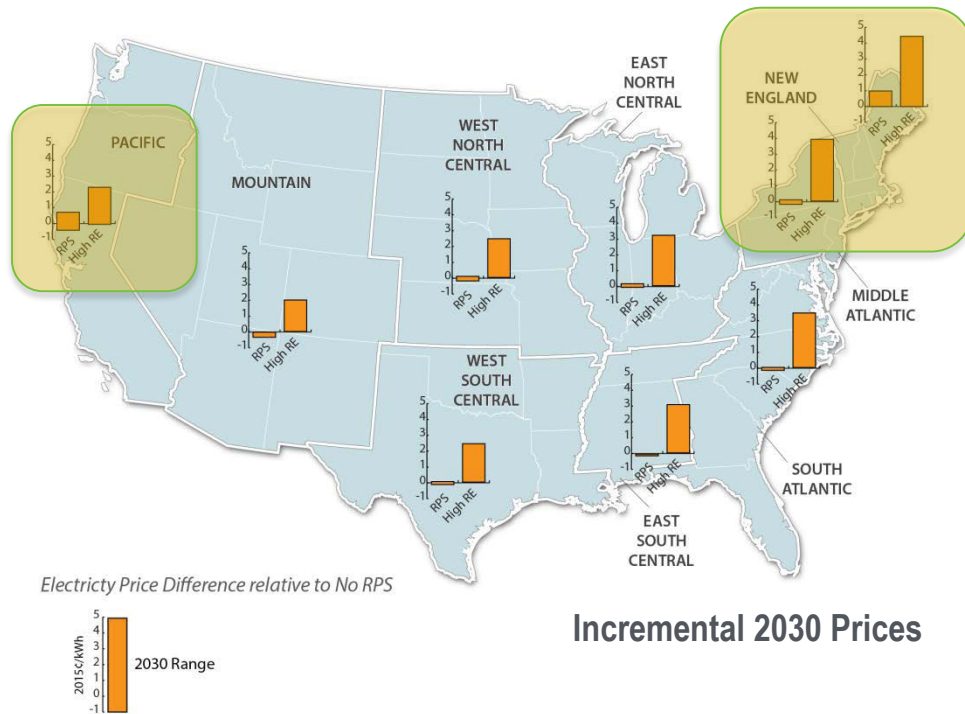


- Existing RPS scenario is found to have an impact of less than $\pm 1\%$ (± 0.75 cents/kWh-RE, $\pm \$31$ billion) across all sensitivities
 - Negative costs (i.e. benefits) indicate that RE is economic beyond the bounding levels set for the No RPS scenario
- Higher RE scenario results in larger incremental costs ranging from 0.6% (\$23 billion) to 4.5% (\$194 billion) (0.25 cents/kWh-RE to 1.5 cents/kWh-RE)

Incremental Electricity Price Estimates Follow a Similar Trend, but Price Impacts Vary by Region



■ High RE
■ Existing RPS



- For the Existing RPS scenarios, 2030 incremental prices fall within ± 0.35 cents/kWh for most regions but with incremental price impacts ranging from -0.4 cents/kWh to nearly 1 cent/kWh in the NE and PA regions
- High RE scenario results in a wide range of possible 2030 incremental prices: from negligible price impacts on the low end up to about 4 cents/kWh in some regions

Air Pollution Emissions and Human Health and Environmental Benefits

Dev Millstein, Ryan Wiser

Estimate combustion-related SO₂ and NO_x emissions impacts (ReEDS)



Estimate combustion-related PM_{2.5} emissions impacts and biopower SO₂, NO_x, and PM_{2.5} (post-processing of ReEDS outputs)



Calculate impacts & monetized benefits of reductions w/ multiple methods (EPA, AP2, EASIUR)

EPA, AP2, EASIUR all account for pollutant transport & chemical transformation as well as exposure & response; each does so differently, considering different impacts

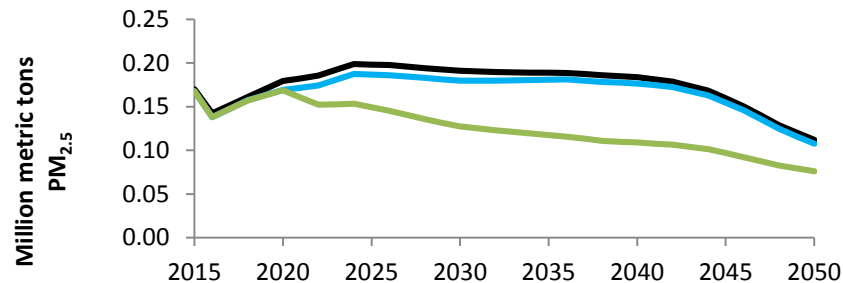
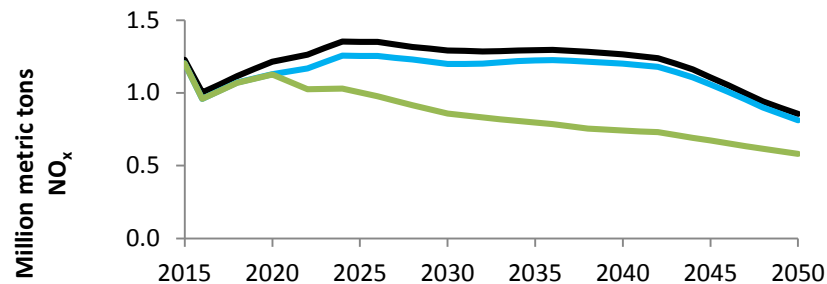
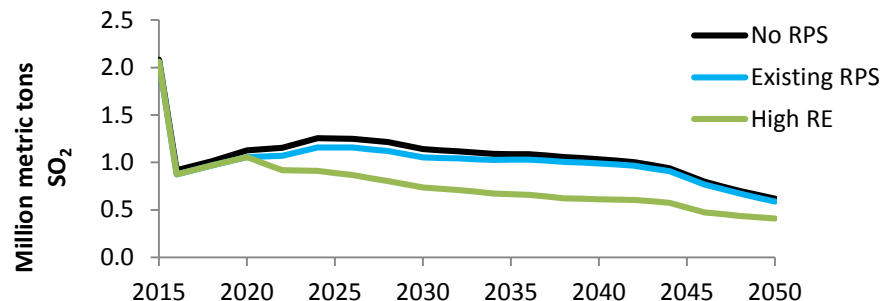
- Focus on subset of air emissions impacts: SO₂, NO_x, and PM_{2.5} emissions, and implications for fine particulate and ozone exposure; only consider plant operations, ignoring life cycle
- ReEDS models air regulations, including CSAPR and MATS, resulting in non-binding caps; actual benefits dictated in part by future regulations, and possible future binding cap-and-trade
- Estimates of health and environmental benefits associated with emissions reductions are uncertain; some of that uncertainty reflected in diversity of methods and estimates
- Do not fully consider erosion of air emissions benefits due to increased cycling, ramping, and part loading required of fossil generators
- Uncertainties in PM_{2.5} and biomass emissions are more substantial than fossil-based SO₂ & NO_x

Summary of Key Results: Physical Impacts

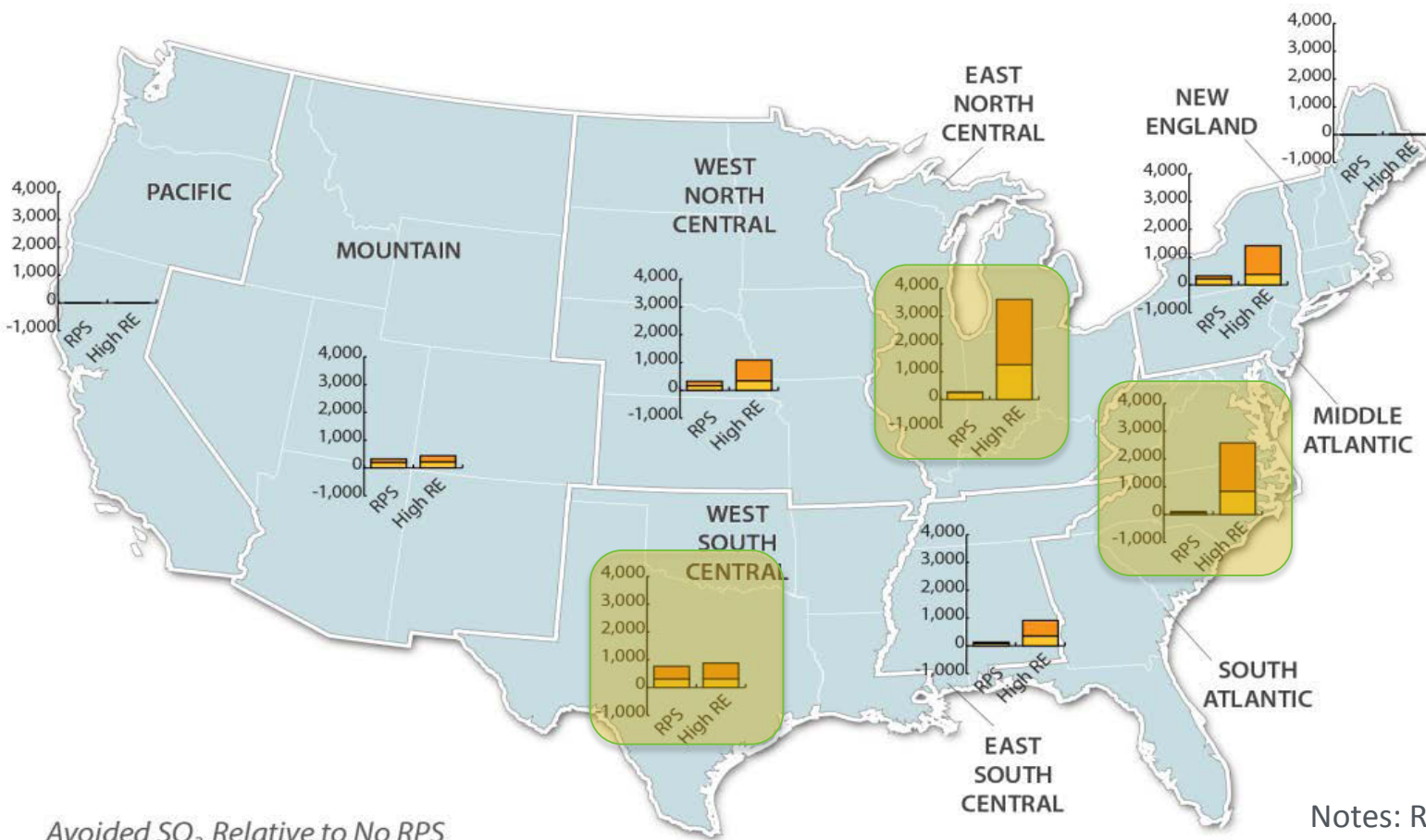
In later years, greater proportions of natural gas are offset, so percentage savings do not grow with time

Cumulative emissions savings under the Existing RPS scenario: 2.1 million metric tons SO₂ (5.5%), 2.5 million metric tons NO_x (5.7%), and 0.3 million metric tons PM_{2.5} (4.5%)

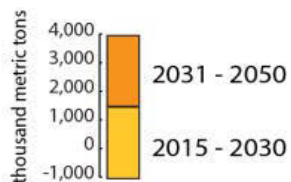
Cumulative emissions savings under the High RE scenario: 11.1 million metric tons SO₂ (29%), 12.8 million metric tons NO_x (29%), and 1.8 million metric tons PM_{2.5} (29%)



Summary of Key Results: Emissions Reductions by Region--SO₂



Avoided SO₂ Relative to No RPS



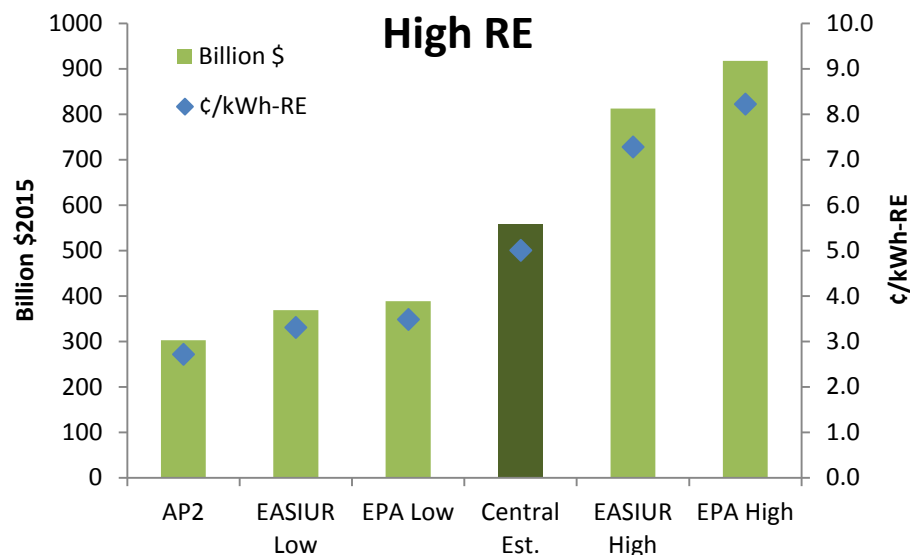
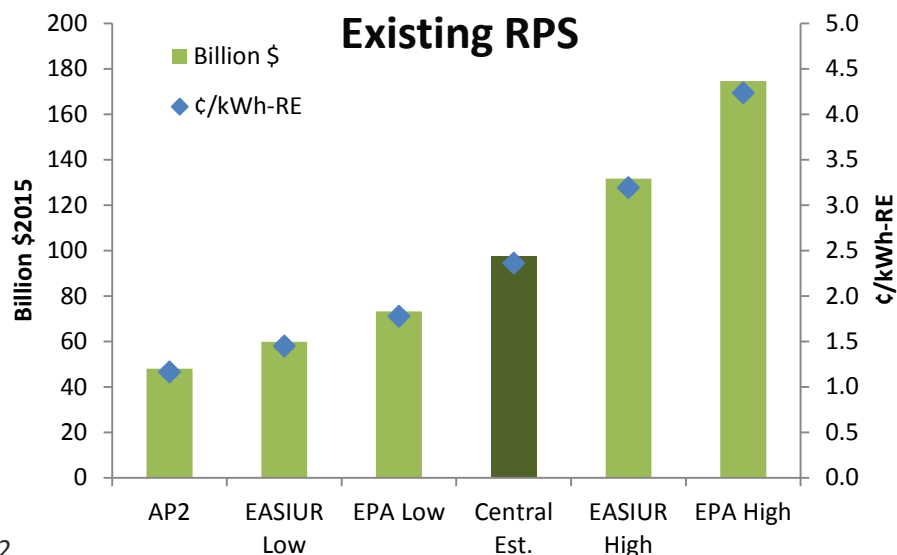
Notes: Regional results for NO_x and PM_{2.5} show similar trends; a few regions with biomass plants serving RPS compliance are estimated to have had small (relative to emission reductions in other states) emission increases

Summary of Key Results: Monetary Benefits

Present-value benefits of Existing RPS scenario (vs. No RPS) range from **\$48 billion to \$175 billion (central = \$97 billion)**; Equivalent to **1.2 to 4.2 ¢/kWh-RE (central 2.4 ¢/kWh-RE)**

Present-value benefits of High RPS Scenario (vs. No RPS) range from **\$303 billion to \$917 billion (Central = \$558 billion)**; Equivalent to **2.7 to 8.2 ¢/kWh-RE (central 5.0 ¢/kWh-RE)**


Majority of benefits derive from reductions in SO₂, and come from reduced premature mortality (12,000-28,000 fewer premature mortalities under Existing RPS, and 70,000-160,000 fewer under High RE)




Greenhouse Gas Emissions Reduction Benefits

Ryan Wiser, Trieu Mai

Estimate combustion-related
CO₂ emissions reductions
(ReEDS)



Estimate GHG emissions
impacts from other life cycle
stages (literature review,
integrated into ReEDS)



Valuation based on: (a) range
of social cost of carbon (SCC),
(b) range of carbon-reduction
compliance-cost estimates

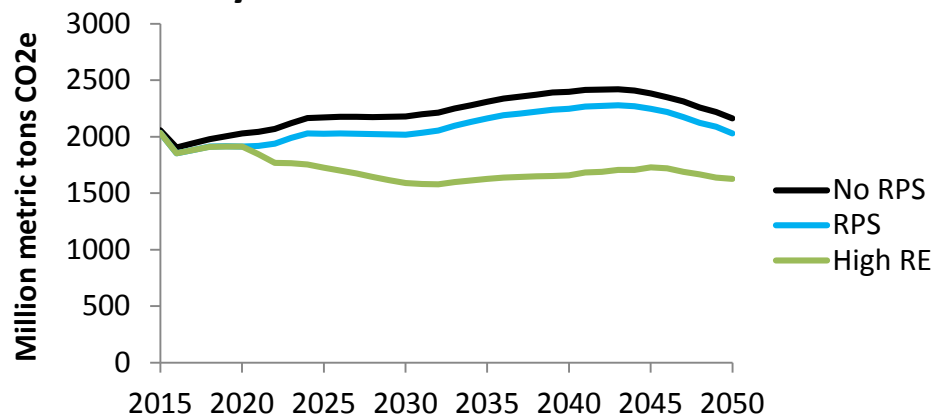
- Rely on 4 SCC estimates from IWG, apply to life-cycle CO₂e; SCC used in federal rulemakings; reflects future global reduced damages to agricultural productivity, human health, property damages, ecosystem services
- Separate valuation based on cost of complying with legal requirements to reduce GHG emissions, under assumption that RE can offset compliance costs; value based on EPA CPP estimates for mass and rate compliance and based on low/medium/high Synapse estimates, using combustion-only emissions
- Both sets of “valuation” estimates are uncertain, as are underlying emissions reduction estimates
- Do not fully consider possible erosion of GHG benefits due to increased operational flexibility of fossil plants
- Indirect land-use emissions from biomass not considered; assume that landfill gas used for electric production would otherwise have been flared

Summary of Key Results: Physical Impacts

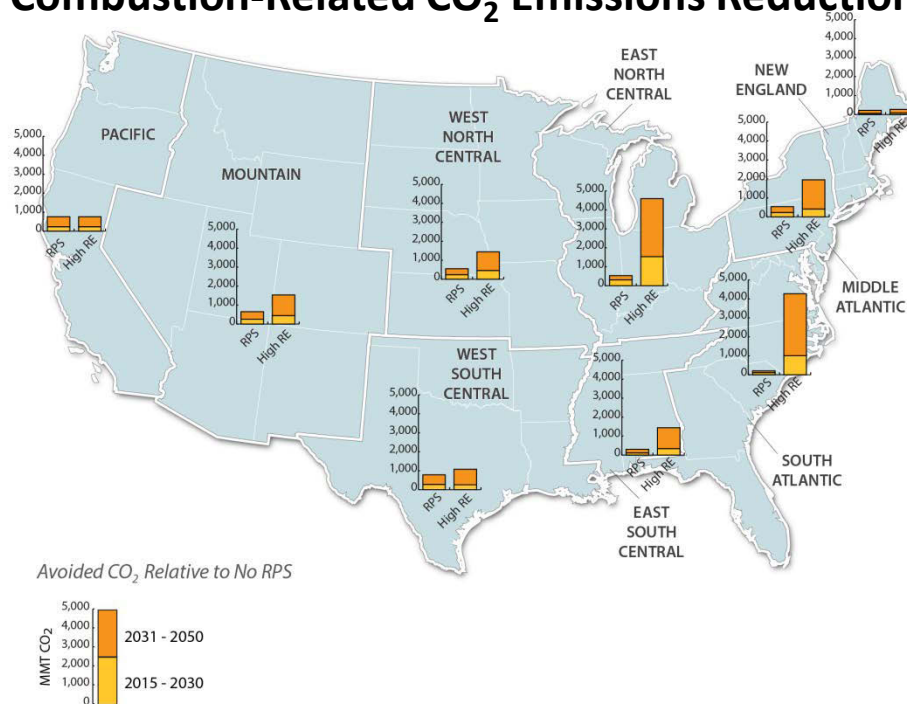
Existing RPS scenario results in life-cycle GHG savings in power sector of 7% in 2030 and 6% in 2050 relative to No RPS

High-RE scenario results in savings of 27% in 2030 and 25% in 2050

Life-Cycle GHG Emissions Reductions

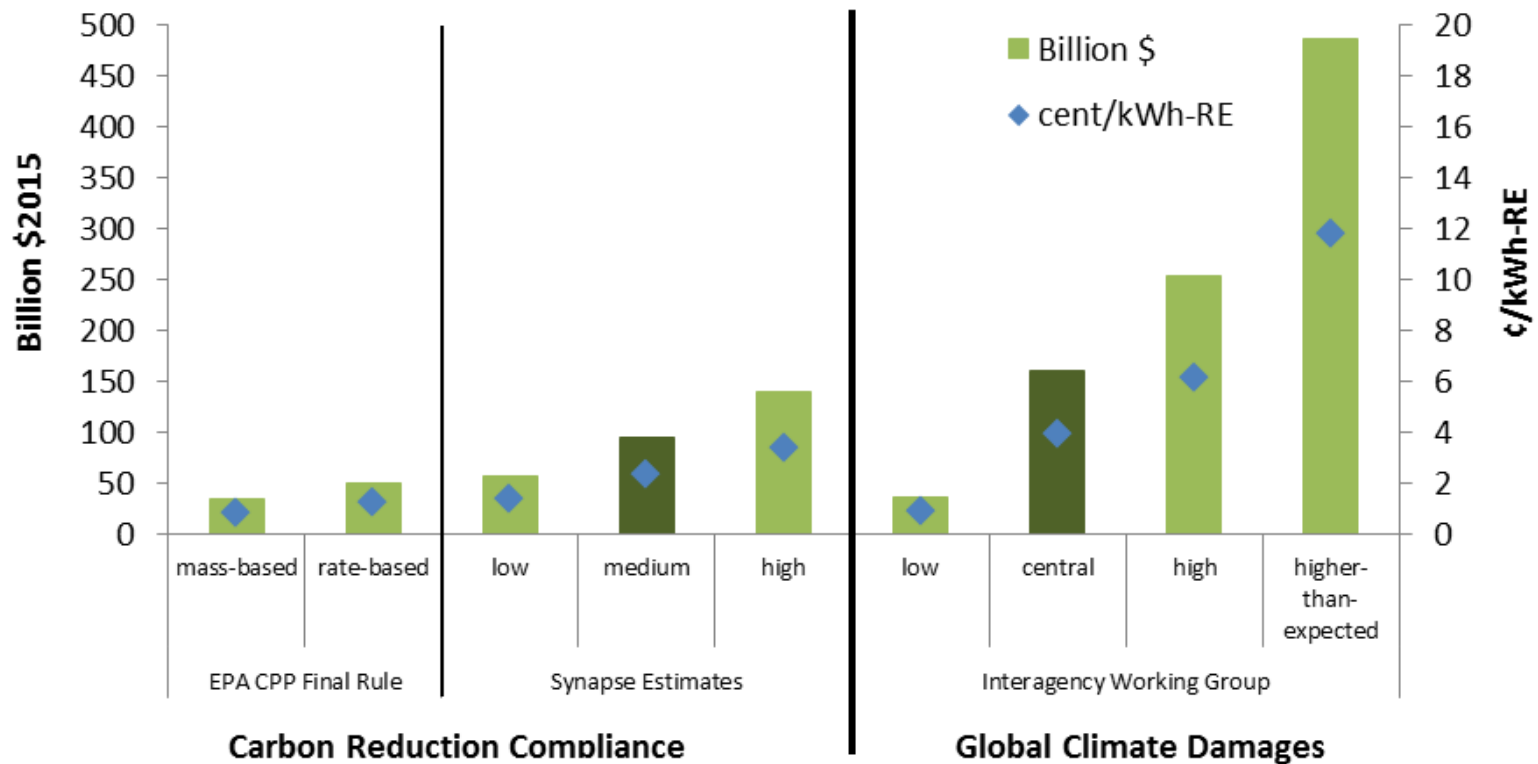


Combustion-Related CO₂ Emissions Reductions



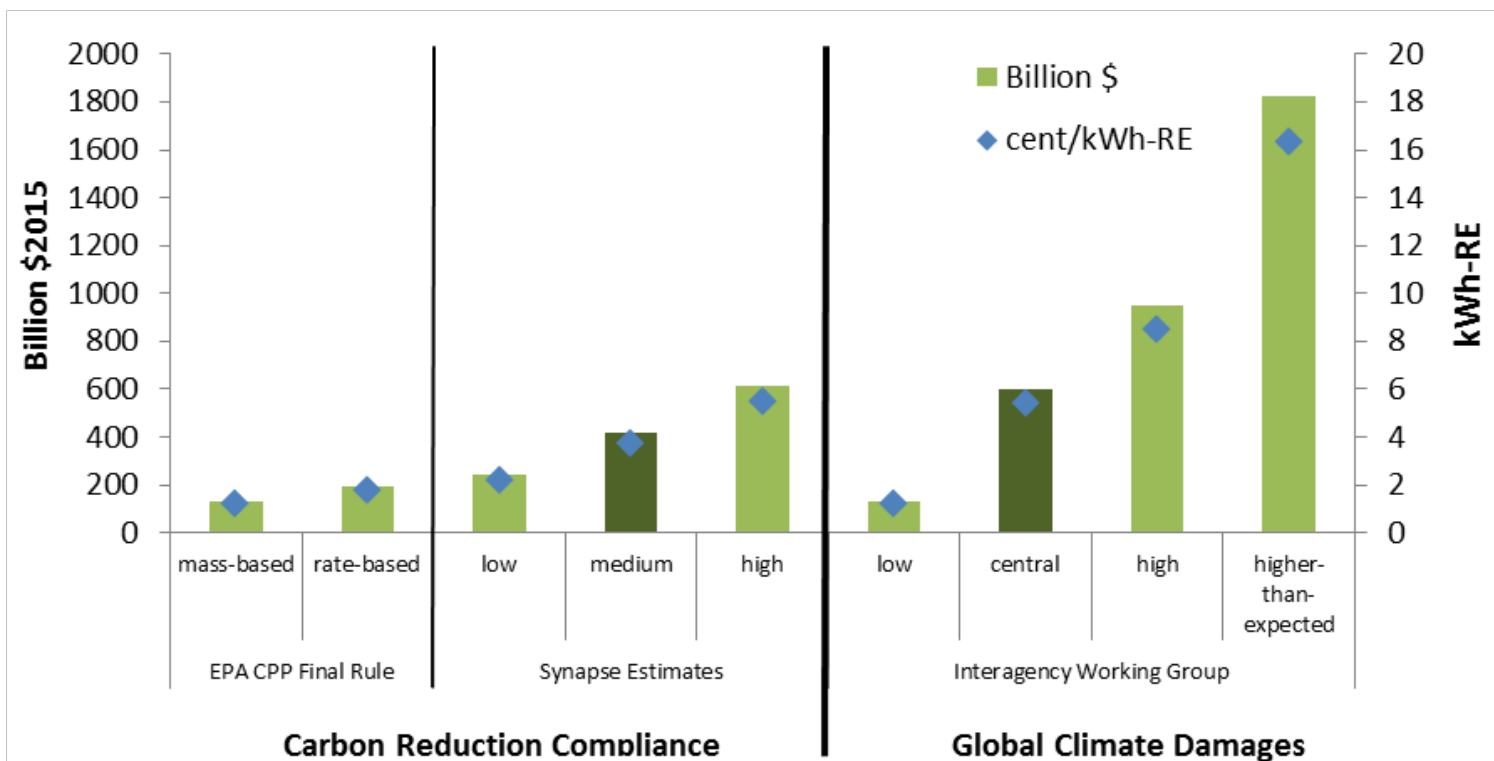
Summary of Key Results: Monetary Benefits, Existing RPS

Present-value benefits of Existing RPS scenario (compared to No RPS) range from \$34 billion to \$140 billion using compliance cost estimates from EPA CPP and Synapse (equivalent to 0.8 to 3.4 ¢/kWh-RE); global damage reduction benefits range from \$37 billion to \$487 billion (**central = \$161 billion**) based on IWG SCC (0.9 to 11.8 ¢/kWh-RE, **central = 3.9 ¢/kWh-RE**)



Summary of Key Results: Monetary Benefits, High RE

Present-value benefits of High RE scenario (compared to No RPS) range from \$131 billion to \$614 billion using compliance cost estimates from EPA CPP and Synapse (equivalent to 1.2 to 5.5 ¢/kWh-RE); global damage reduction benefits range from \$132 billion to \$1,821 billion (**central = \$599 billion**) based on IWG SCC (1.2 to 16.3 ¢/kWh-RE, **central = 5.4 ¢/kWh-RE**)



Water Use Reduction Benefits

Jordan Macknick

Estimate renewable and fossil changes in generation (ReEDS)



Estimate cooling technology and water withdrawal and consumption by region (ReEDS)



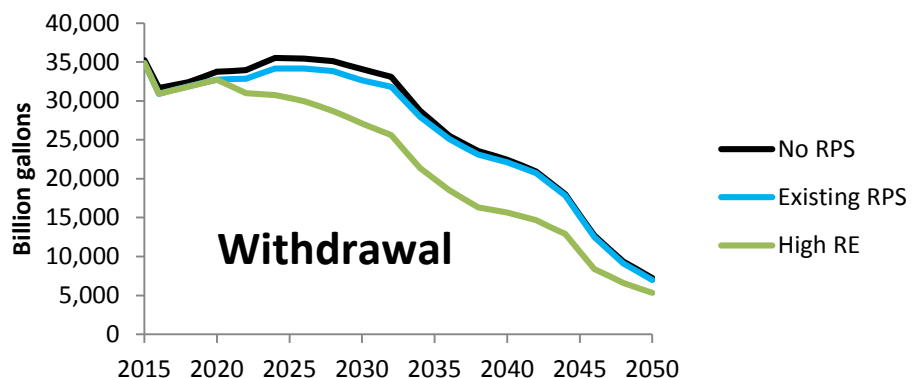
Quantify national and regional net water use reductions

Considers operational water withdrawal and consumption of all fossil, nuclear, and renewable energy sources

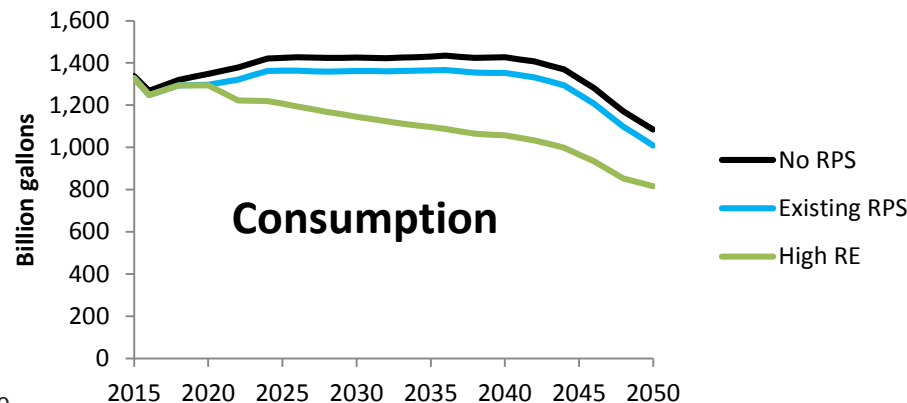
- Do not quantify benefits of water use reductions in monetary terms: methodological challenges
- Only consider operational water use and do not estimate full life cycle uses; including upstream uses would likely increase RPS benefits
- Assessment relies on assumptions about which prime mover technology type and cooling system is associated with individual generators
- Biomass (non-gas) sources are assigned water use characteristics of simple-cycle steam turbine solid-biomass power plants, biomass (gas) sources are assigned characteristics of biogas-based power plants, and landfill gas plants are assumed to require no water for operations
- Do not consider hydropower evaporation due to uncertainties in allocation among multiple uses

Summary of Key Results: Physical Impacts, National

Existing RPS scenario results in reduced national operational water withdrawals / consumption in the U.S. power sector of **4%/4% in 2030** and **3%/7% in 2050** relative to No RPS scenario; High-RE scenario results in savings of **20%/20% in 2030** and **26%/25% in 2050**



2030 consumption savings = annual water use of 420,000 U.S. households for the Existing RPS scenario; 1.9 million households for High RE scenario

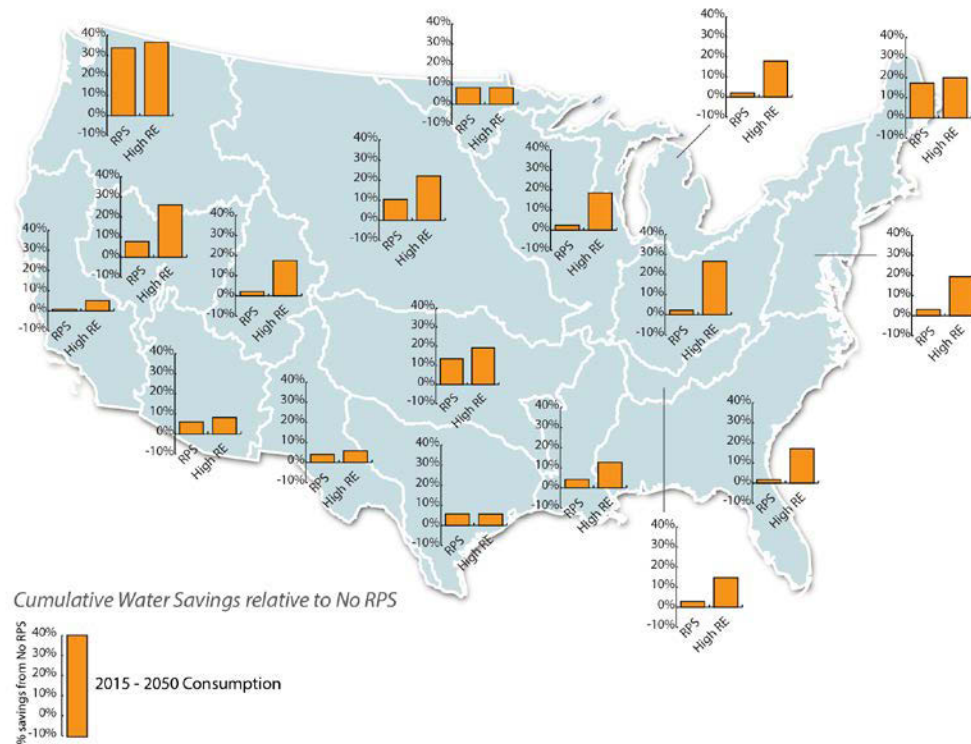


Cumulatively (2015-2050), each MWh of RE serving existing RPS represents average savings of 3,400 gallons of water withdrawal and 290 gallons of consumption

Summary of Key Results: Regional Water Consumption Savings

- Amount of water savings is affected by the amount and type of incremental RE supply and by the water use associated with the displaced fossil units
- Water consumption (and withdrawal) declines more under Existing RPS and High RE scenarios than under No RPS scenario in most watershed regions
- The largest water savings, especially under the High RE scenario, are from regions that currently withdraw and consume larger amounts of water for power generation

Percent cumulative consumption savings



Summary of Key Results: Monetary Benefits

Standard methods do not exist to value—in monetary terms—water use benefits, but water use reductions can be considered a co-benefit of RE deployment, especially where water is scarce

- Reduce 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
- Frees water for other uses, whether for other productive economic purposes or to strengthen local ecosystems
- By avoiding upstream water demands from fossil fuel supply, RE can help alleviate other energy-sector impacts on water resource quality and quantity

Gross Renewable Energy Workforce Requirements

David Keyser

Incremental renewable generation,
capacity, and investments during
2015-2050 (ReEDS)



JEDI models and IMPLAN



Gross jobs, earnings, output, and
GDP impact estimates

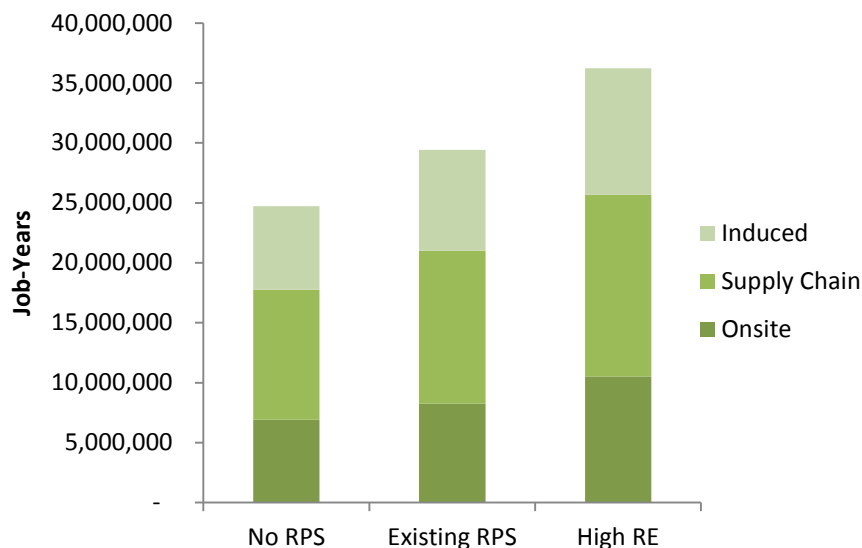
JEDI used for all estimates, except for landfill gas, where IMPLAN is used instead; costs and assumptions for “domestic content” largely based on JEDI default data

- Results are reported based on onsite, supply chain, and induced impacts, for both operation and construction; results presented on a national and, for onsite jobs only, on a regional basis
- All results produced by JEDI and IMPLAN are for the equivalent of a single year—O&M jobs can be assumed to be ongoing, however, while construction jobs are inherently limited
- Estimates represent gross impacts: do not reflect other potential economic impacts such as displaced fossil plants, changes in utility electricity rates, or changes in property values or other prices—results should not be considered net economy-wide impacts or societal benefits
- Inherent uncertainty due to unknown future changes in technology and the economy

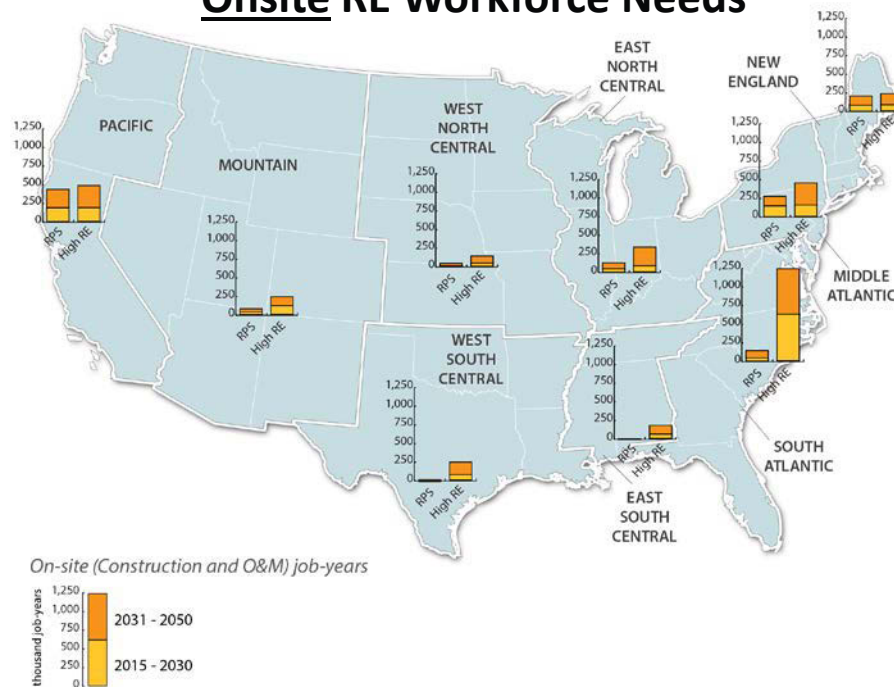
Summary of Key Results: RE Workforce Requirements

- The Existing RPS scenario relative to No RPS scenario requires 4.7 million additional RE-related job-years; a 19% boost in RE-related employment and equivalent to an average of 134,000 more workers annually
- The High RE scenario requires 11.5 million additional RE-related job-years; a 47% boost in RE-related employment
- Location of onsite jobs affected by level of RE deployment and labor intensity of the specific RE technologies deployed in each region

Total RE Workforce Requirements

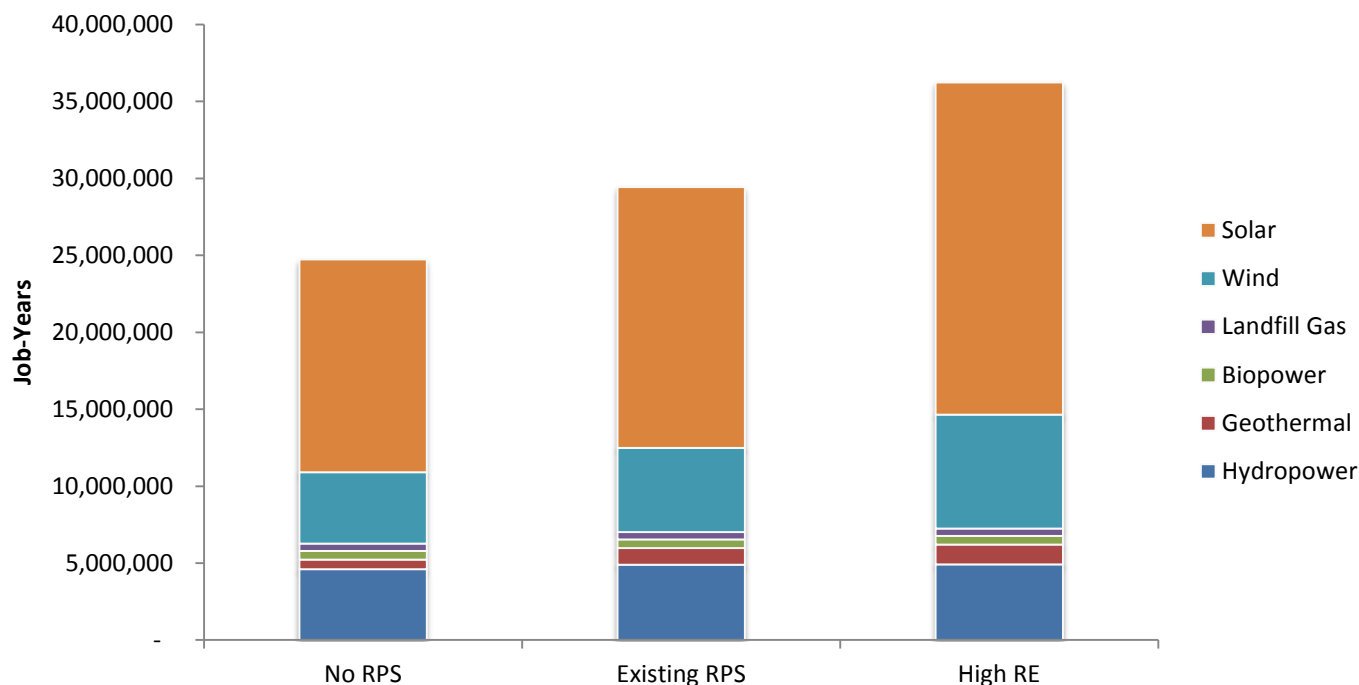


Onsite RE Workforce Needs



Summary of Key Results: Details on Impacts

- Distribution of RE workforce needs among RE technologies reflects expansion as well as characteristics of operation and construction: some technologies are more labor intensive than others
- Most incremental deployment and jobs in solar PV and wind



Natural Gas Price Reduction Impacts

Trieu Mai

Derive regional "inverse price elasticity of natural gas" supply curve from EIA AEO



Implement in ReEDS, and estimate regional natural gas prices in all scenarios (ReEDS)



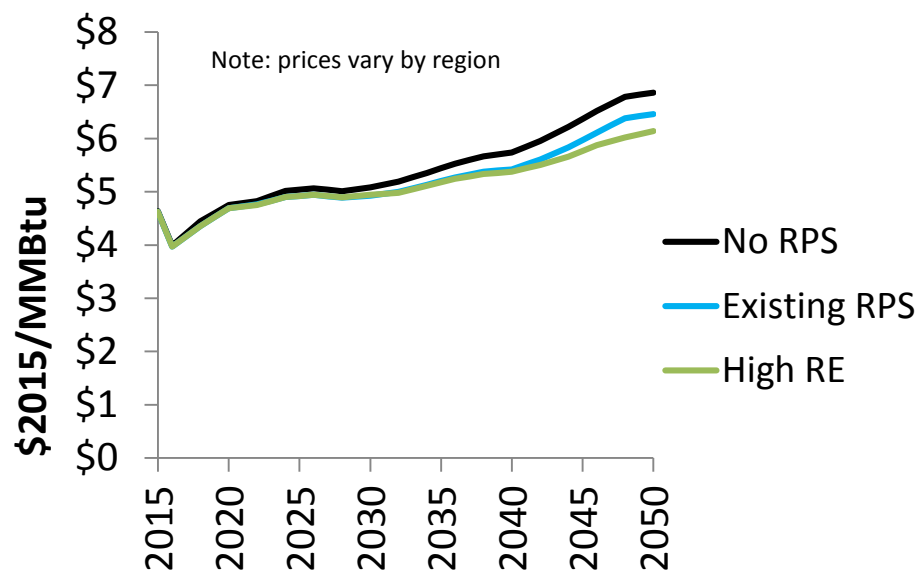
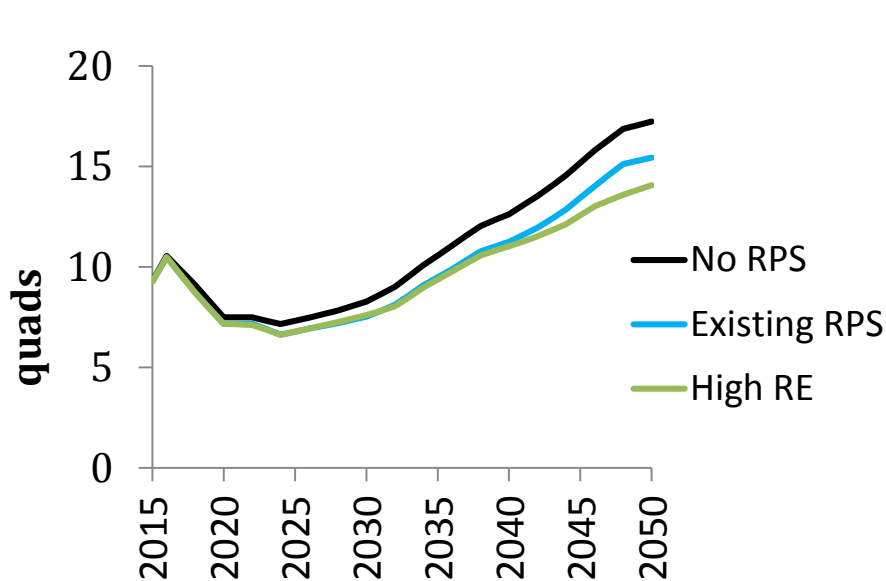
Apply resulting natural gas price changes to forecast of regional natural gas demand outside of power sector (EIA)

- Consumer benefits calculated here represent a wealth transfer from producers to consumers: no net societal benefit is claimed, at least nationally
- Natural gas price reductions in power sector are accounted for in "cost" impacts earlier; focus here is on impact of reductions outside power sector
- Though roughly consistent with past literature, the accuracy of the inverse elasticity curves derived from EIA AEO are uncertain
- Assume that national average wellhead price changes flow through fully to delivered gas prices in all regions and sectors; assume that consumers are 100% exposed to wellhead price changes
- Do not fully account for possible rebound effect whereby gas price reductions spur additional demand

Summary of Key Results: Physical and Price Impacts

Existing RPS scenario results in reduced demand for natural gas by 35 quads from 2015-2050, representing 3.3% of total consumption in U.S. as estimated and extrapolated from the AEO 2016 Reference case: lowered gas prices by \$0.36 to \$0.59/MMBtu in 2050 across all regions

Cumulative reductions in the High RE scenario total 46 quads (4.3%) and lowered gas prices by \$0.69 to \$0.89/MMBtu in 2050

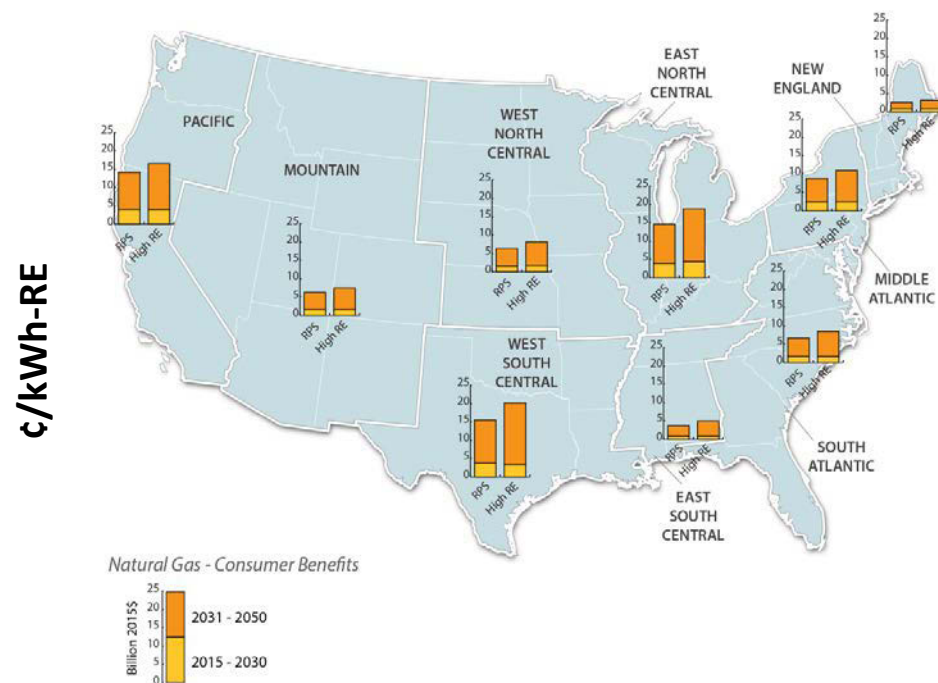
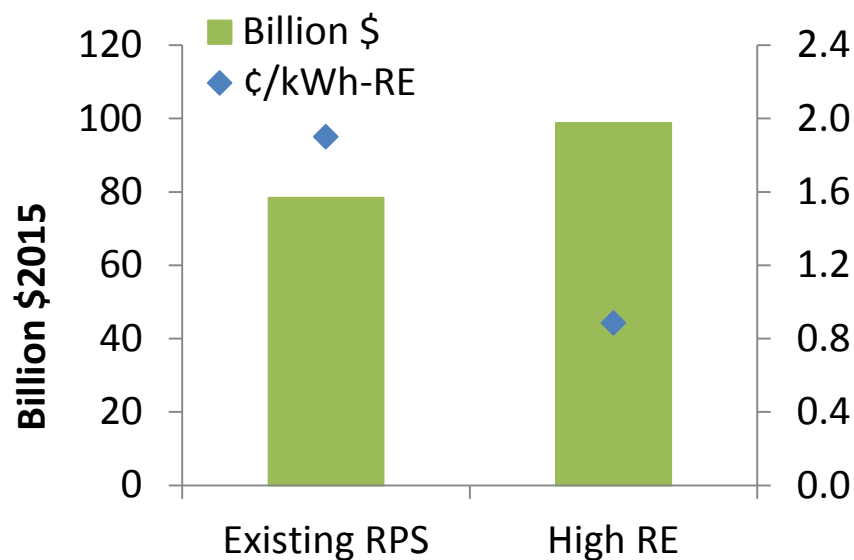


Summary of Key Results: Monetary Impacts

When lower gas prices are applied to all non-electric gas-consuming sectors of the economy, aggregate present-value consumer savings are estimated to be:

- Existing RPS: \$78 billion (1.9 ¢/kWh-RE)
- High RE: \$99 billion (0.9 ¢/kWh-RE)

Consumer benefits vary by region depending on regional gas price reduction and delivered gas consumption in each region



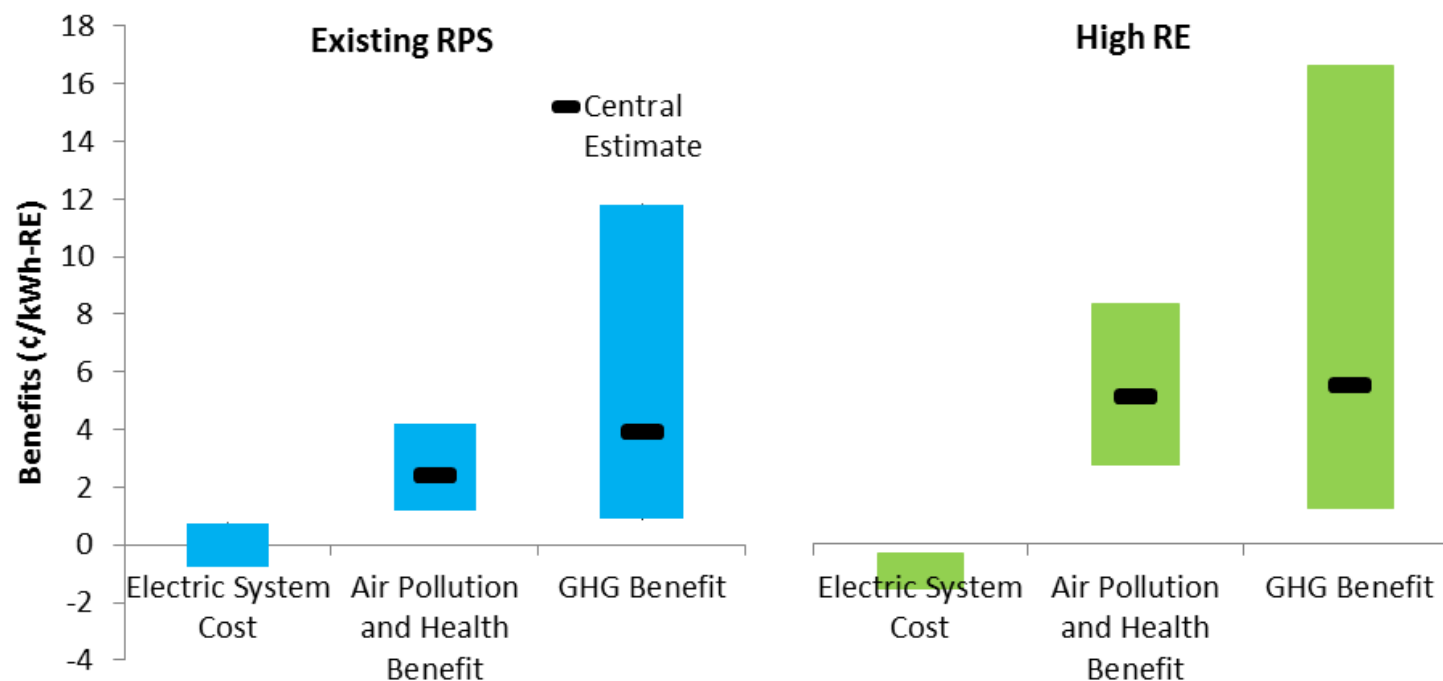
Summary and Conclusions

Summary of Prospective Costs, Benefits, and Impacts of RE Supported by State RPS Policies

		EXISTING RPS		HIGH RE	
RENEWABLE ENERGY IN 2050		Increased by ↑ 122 GW 296 TWh		Increased by ↑ 331 GW 765 TWh	
COSTS	ELECTRIC SYSTEM COSTS	range from -0.7% to 0.8%	equivalent to +/- \$31 billion <small>estimates span +/- 0.75¢/kWh-RE</small>	range from 0.6% to 4.5%	equivalent to \$23 billion- \$194 billion <small>estimates span 0.26-1.5¢/kWh-RE</small>
	ELECTRICITY PRICES	range from -2.4 cents/kWh to 1 cent/kWh		range from -1.9 cents/kWh to 4.2 cents/kWh	
BENEFITS	SULFUR DIOXIDE	reduced by ↓ 6%	2.1 million metric tons SO ₂	reduced by ↓ 29%	11.1 million metric tons SO ₂
	NITROGEN OXIDES	reduced by ↓ 6%	2.5 million metric tons NO _x	reduced by ↓ 29%	12.8 million metric tons NO _x
	PARTICULATE MATTER 2.5	reduced by ↓ 5%	0.3 million metric tons PM _{2.5}	reduced by ↓ 29%	1.8 million metric tons PM _{2.5}
	GREENHOUSE GAS EMISSIONS	reduced by ↓ 6%	4.7 billion metric tons CO _{2e}	reduced by ↓ 23%	18.1 billion metric tons CO _{2e}
	WATER USE	reduced by ↓ 4% consumption	3% withdrawal	reduced by ↓ 18% consumption	18% withdrawal
IMPACTS	NATURAL GAS	reduced by ↓ 35 quads (3.3%)	equivalent to \$78 billion impact 1.9¢/kWh-RE	reduced by ↓ 46 quads (4.3%)	equivalent to \$99 billion impact 0.9¢/kWh-RE
	RE JOB NEEDS	increase in ↑ 19% RE-employment	equivalent to 4.7 million RE job-years	increase in ↑ 47% RE-employment	equivalent to 11.5 million RE job-years

- Relying on a well-vetted set of methods, the study evaluates the costs, benefits, and other impacts of renewable energy used to meet future RPS demand growth—from current state RPSs as well as under a high RE scenario in which most states adopt aggressive targets—over the 2015-2050 period
- We find 296 TWh (122 GW) of new RE generation is needed to meet Existing RPSs; 765 TWh (331 GW) is needed under the High RE scenario
- Incremental RE generation offsets fossil generation leading to environmental benefits (air pollution, GHG, water) and other impacts

Comparison of Costs and Monetized Benefits



- When comparing the costs and monetized benefits, we find that the benefits exceed the costs, even when considering the highest cost and lowest benefit outcomes
 - Existing RPS: Costs are <0.75 cents/kWh-RE vs. >1.2 cents/kWh-RE air pollution and >0.9 cents/kWh-RE GHG benefits
 - High RE: Costs are <1.5 cents/kWh RE vs. >2.7 cents/kWh-RE air pollution and >1.2 cents/kWh-RE GHG benefits
- Additional benefits occur from water savings, which could not be readily monetized; other impacts associated with gross RE workforce needs and natural gas consumers are also quantified
- Important to recognize that RPS policies may not be the least-cost means of achieving these benefits; see “limitations” noted earlier and described in full report

For more information...

Report, summary fact-sheet, and PPT briefing are all available:

- <http://www.nrel.gov/docs/fy17osti/67455.pdf>
- <https://emp.lbl.gov/publications/prospective-analysis-costs-benefits>

Related reports, data, and materials are also available:

- <http://www.nrel.gov/analysis/rps.html>
- <http://rps.lbl.gov>

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