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Jaquelin Cochran, Paul Denholm, Bethany Speer, and Mackay Miller
National Renewable Energy Laboratory

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Abstract

In the United States and elsewhere, renewable energy (RE) generation supplies an increasingly large percentage of annual demand, including nine U.S. states where wind comprised over 10% of in-state generation in 2013. This white paper summarizes the challenges to integrating increasing amounts of variable RE, identifies emerging practices in power system planning and operation that can facilitate grid integration, and proposes a unifying concept—*economic carrying capacity*—that can provide a framework for evaluating actions to accommodate higher penetrations of RE.

There is growing recognition that while technical challenges to variable RE integration are real, they can generally be addressed via a variety of solutions that vary in implementation cost. As a result, limits to RE penetration are primarily economic, driven by factors that include transmission and the flexibility of the power grid to balance supply and demand. This limit can be expressed as *economic carrying capacity*, or the point at which variable RE is no longer economically competitive or desirable to the system or society.

Power systems already have some degree of operational flexibility, an ability to respond to change in demand and supply, as they must accommodate variable and uncertain load. Power system operators have thus been able to accommodate increased variable RE largely without substantial new investment in system flexibility, such as new storage, demand response, or generation dedicated to addressing RE variability and uncertainty. To achieve higher penetration levels, multiple grid integration studies in the United States have evaluated scenarios where an economic carrying capacity of at least 30% is achieved via transmission expansion and largely understood changes to system operations. Studies have also demonstrated that carrying capacity is not fixed and can be improved through technical and institutional changes. This creates the possibility to achieve even higher penetration levels through strategic investments in both demand- and supply-side sources of flexibility.

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Table of Contents

Figures and Tables

1 Introduction

In the United States and elsewhere, renewable energy (RE) generation supplies an increasingly large percentage of annual demand, including nine U.S. states where wind comprised over 10% of in-state generation in 2013 (Wiser and Bolinger 2014). Variable RE—primarily wind and solar—account for the majority of newly-built RE capacity in the United States (Esterly 2014).

Compared to conventional thermal generation, wind and solar are marked by five characteristics of particular concern to power grid operators: variability, uncertainty, location-specificity, non-synchronous generation, and low capacity factor. Due to these characteristics and the rapid increase in deployment, the operation and planning of power systems are evolving, and grid integration of renewable energy has become a focal point of national and international research and collaboration.

This white paper summarizes the challenges to integrating variable RE, identifies emerging practices in power system planning and operation that can facilitate grid integration, and proposes a unifying concept—*economic carrying capacity*—that can provide a framework for evaluating actions to accommodate higher penetrations of RE. The appendix provides an overview of the U.S. renewable electricity market.

The concept of carrying capacity has evolved over time. While historically there has been a perception that physical or technical issues will fundamentally limit the penetration of variable RE, recently conducted grid integration studies and operational experience have created a more nuanced understanding. Specifically, there is growing recognition that while technical challenges to variable RE integration are real, they can generally be addressed with a variety of solutions, each with an associated implementation cost. As a result, the limit to RE penetration is primarily economic, driven by factors that include transmission availability and operational flexibility, which is the ability of the power grid to balance supply and demand. This limit can be expressed as *economic carrying capacity*, or the level of variable RE generation at which that generation is no longer economically competitive or desirable to the system or society.[1] The economic carrying capacity of any power system is highly region-specific and can change over time, for example, as inflexible generators retire, demand and renewable supply forecasting improves, market designs evolve, or as enabling technologies become more affordable (e.g., storage).

The recognition that technical and institutional changes could improve economic carrying capacity provides a framework for developing strategic investments and updating grid management practices across the U.S. energy landscape. System-specific research and analysis to develop a more precise understanding of grid integration dynamics could enable greater grid integration at lower costs, and would enhance U.S. international leadership in RE deployment.

[1] Economic carrying capacity is a distinct concept from effective load carrying capacity, which is the amount by which a system's loads can increase when a generator is added to the system while maintaining the same reliability.

2 Grid Integration of Variable RE: Overview

2.1 Impacts of Variable RE on System Operations and Planning

Renewable energy generated from variable sources such as wind and solar offers a low-carbon source of electricity. At high penetration levels, the challenges of variable RE must be considered in the planning and operation of the power grid. Variable renewable electricity possesses five characteristics of particular concern to power grid operators, as described in Table 1.

Table 1. Characteristics of Power from Variable RE Sources, Potential Grid Integration Challenges, and Mitigation Options

Wind and Solar Characteristics		Potential Grid Integration Challenges	Mitigation Options
Variability	Generator output can vary as underlying resource fluctuates.	Balancing generation with electricity load requires more flexibility.	In many power systems, sufficient flexibility exists to integrate additional variability, but this flexibility may not be fully accessible without changes to power system operations or other institutional factors (e.g., increased ramping of generation and improved coordination across markets and balancing areas) (Lew et al. 2013).
Uncertainty	Generation cannot be predicted with perfect accuracy (day-ahead, day of).	System operators could need additional reserves and/or an improved ability to dispatch generation.	Integration of advanced renewable supply forecasting into dispatch and market operations has reduced uncertainties, improved scheduling of other resources to reduce reserves and fuel consumption, and enabled variable RE to participate as dispatchable resources (IEA 2014; Lew et al. 2011). Examples: Xcel Energy, U.S. RTOs/ISOs (Porter et al. 2012).[2]
Location-specificity	Generation is more economical where highest quality resources are available.	More transmission and more advanced planning could be needed.	Competitive Renewable Energy Zones (CREZ) in Texas are an example of an approach to quickly develop generation and transmission in coordination (18.5 GW—3,600 miles—completed nine years after CREZ legislation was signed), to access wind resources in remote parts of the state.
Non-synchronous generation	Generators provide voltage support and frequency control in a different manner than traditional resources.	Voltage and frequency stability from variable RE generators or additional equipment comes at added capital and/or opportunity costs.	Grid code[3] requirements are evolving in response to technological advances and anticipation of high RE penetration levels. For example, ERCOT, which is a small interconnection and more vulnerable to frequency excursions, now requires wind generators to provide inertial response, which helps keep a system stable in the initial moments after a disturbance (Bird, Cochran, and Wang 2014).
Low capacity factor	Availability of the underlying energy resource limits the run-time of the plant.	Existing conventional generators could be needed to meet demand, but run less than originally anticipated, affecting cost recovery.	Capacity payments or markets, potentially tied to flexible performance, could ensure sufficient cost recovery. The potential for stranded assets is not unique to variable RE, and can occur whenever generation with lower marginal costs is added to the system. For example, low natural gas prices have reduced the market competitiveness of nuclear plants, contributing to recent retirements (Wernau and Richards 2014).

[2] The U.S. regional transmission organizations (RTOs) and independent system operators (ISOs) are California ISO (CAISO), Electric Reliability Council of Texas (ERCOT), ISO New England (ISO-NE), Midcontinent ISO (MISO), NYISO (formally New York ISO), PJM Interconnection (PJM), and Southwest Power Pool.
[3] Grid codes establish the performance requirements of a grid-connected generator including response during a system disturbance.

Figure 1 demonstrates how variability can impact power system operations, and introduces the concept of net load—i.e., the demand that must be met by other generation sources if all wind and solar power is consumed (Milligan 2011). All power systems have some level of variability, even without the presence of wind and solar generators, and require flexibility in system operations and generation to rapidly manage changing system conditions.

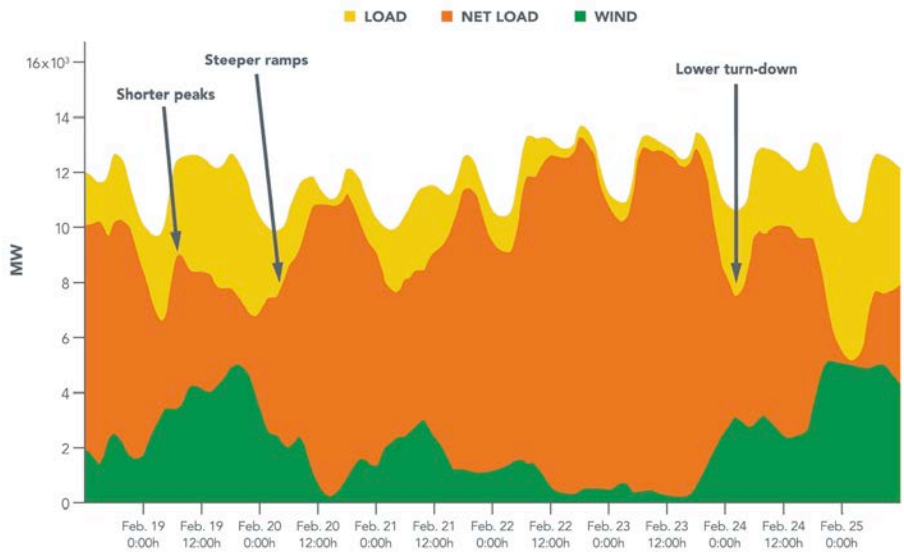

Figure 1. Greater need for operational flexibility
Source: Cochran et al. 2014[4]

Wind and solar generation can create the need for more flexibility. This figure illustrates how wind generation can lead to steeper ramps, deeper turn downs, and shorter peaks in system operations.

Ramps **-** The rate of increase or decrease in dispatchable generation to follow changes in net load. Ramps can be steep if wind generation is decreasing at the same time that demand rises.

Turn-downs **-** Operation of dispatchable generators at low levels. High wind output during periods of low demand creates a need for generators that can turn down output to low levels but remain available to rise again quickly.

Shorter peaks – Periods during which generation is supplied at a higher level. Peaks are shorter in duration, resulting in fewer operating hours for conventional plants, affecting cost recovery and long-term security of supply.

Flexibility can reduce the need to curtail (decrease the output of) solar and wind output; improve investor confidence in RE and revenue streams; decrease the risk of negative market pricing (which results when conventional generators cannot sufficiently reduce output during times of oversupply); and reduce environmental impacts by increasing system efficiency and maximizing the utilization of clean RE. See Text Box 1 for example indicators of a lack of flexibility, or inflexibility, on a system.

[4] Another example is the CAISO "duck curve" showing ramping requirements of up to 13,000 MW in three hours in the period around sunset (CAISO 2013). See http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

Text Box 1. System Inflexibility Indicators

Examples of inflexibility are more commonly documented than flexibility.

Indicators of inflexibility include:

Difficulty balancing demand and supply, resulting in violations to Area Control Error (i.e., deviations from schedule of the area power balance), frequency excursions, or dropped load.

Significant renewable energy curtailments, occurring when available generation is routinely not fully utilized on the system due to transmission constraints or when output of other generation cannot be reduced.

In addition, in competitive wholesale markets:

Negative market prices, which can signal several types of inflexibility, including conventional plants that cannot reduce output, load that cannot absorb excess supply, surplus RE generation, and limited transmission capacity to balance supply and demand across broader geographic areas. Negative prices can occur in systems without RE but may be exacerbated as RE penetration increases.

Electricity price volatility (the variation of price over time), which can reflect limited transmission capacity; limited availability of ramping, fast response, or peaking supplies; or limited ability for load to reduce demand.

Source: Cochran et al. 2014

2.2 Emerging Best Practices

Despite these grid integration challenges, many countries have integrated high levels of variable RE as a share of annual electricity generated.[5] In these systems the impact of variable RE has not compromised reliability because policy makers, planners, and system operators have made changes to regulations, market designs, and system operations to address the grid integration challenges. While there is no "one-size-fits-all" approach, these experiences have informed a set of best practices that address the grid integration challenges. These best practices include improving integrated planning methodologies and increasing system flexibility.

2.2.1 Improve Integrated Planning Methodologies

Coordinated and integrated planning allows decision makers to anticipate how variable RE might impact the power grid and its operations, and evaluate options that could minimize costs across a system. Planning that is segregated by type (e.g., generation, transmission, and system performance each evaluated separately) or restricted to a small geographic scale adversely impacts the ability to employ best practices to accommodate RE, including diversifying RE locations and enlarging balancing authorities (Cochran et al. 2012). For example, the addition of new physical generation capacity can be minimized if considered in coordination with improvements to system operations that increase access to existing flexibility. Also, co-optimized development of transmission and RE generation can reduce overall costs of transmission, and facilitate lower-cost access to high-quality RE resources (see, for example, Competitive RE Zones in Texas and Irish "Gate Process" or group-processing approach in Miller et al. 2013). Regarding geographic scale, FERC Order 1000 compels U.S. states to participate in regional transmission planning (FERC 2014).

[5] Example power systems with high variable RE penetration levels include Denmark (39% from wind in 2014) (The Local 2015), Spain (20.9% from wind), and Italy (7.8% from solar PV) (REN21 2014).

2.2.2 Increase System Flexibility Across All Elements of the Power System

Although simple-cycle natural gas plants, which can be designed to change output quickly, are frequently viewed as a natural pairing with variable RE, other sources of flexibility may already exist across the power system: operations, demand, energy storage, generation, and transmission.

Flexible system operations and markets: Two central components to system operation are unit commitment and dispatch. Unit commitment is the scheduling of generators to be available, typically day-ahead. Dispatch is the method by which system operators choose among available generators to deliver energy at least operating cost. The system operator seeks to access the physical system (e.g., generators) in the most flexible manner. But access to the physical system is mediated by the institutional framework, namely the rules for how decisions are made in scheduling and dispatch. Changes to system operation practices and markets can allow access to significant existing flexibility, often at lower economic costs than options requiring new sources of physical flexibility (IEA 2014; Cochran et al. 2014). For example, establishing short-term market products for flexible generation (e.g., CAISO and MISO's proposed ramping products) can help ensure that existing physical flexibility is available when needed (Abdul-Rahman et al. 2012).

As another example, incorporating renewable supply forecasting into unit commitment and dispatch can improve the scheduling of other generators to reduce reserves, fuel consumption, and operating and maintenance costs (Lew et al. 2011). Regulations increasingly require variable RE generators to forecast power output and the potential for forced outages (FERC 2012). Integrating these data into market operations can help variable RE plants participate efficiently in electricity markets (Reisz and Milligan 2014).

Additional examples of operational changes that improve access to flexibility include a higher dispatch frequency (the timeframe over which a generator must follow a specified output level) (Milligan et al. 2011) and use of smart network technologies and advanced network management practices that minimize bottlenecks and optimize transmission usage (Miller et al. 2013).

Flexible demand and energy storage: Demand response—increasing the responsiveness of electricity demand to operator controls and/or price signals—improves flexibility by enabling or encouraging consumers, particularly in the industrial and commercial sectors, to vary their demand in response to system events or economic conditions (Hummon and Kiliccote 2013). Demand response mechanisms include automated load control by the system operator, real-time pricing, and time-of-use tariffs. A typical response time for automated demand response is seconds to minutes (Watson et al. 2012). Although participation by individual customers might be limited in duration (e.g., a few hours a year), aggregating participation over a broad customer class can provide a reliable source of system flexibility. For example, ERCOT has broadened its demand response program, which now includes loads as resources that bid in both energy and ancillary services markets, loads that are willingly interrupted during emergencies and loads that adjust output in response to price signals from their retail electricity providers. Demand response can be inexpensive but requires new regulations related to response time, minimum magnitude, reliability, and verifiability of demand-side resources (Cappers et al. 2012).

Additionally, energy storage technologies—including pumped hydroelectric, compressed air, thermal storage, and batteries—also hold value at high penetrations of variable RE (Denholm et al. 2013). Storage can absorb energy when its value is low, reduce RE curtailment, and provide additional operational flexibility through its fast response time. Many storage technologies (e.g., batteries, flywheels, supercapacitors) have fast response rates (seconds to minutes) available over a short timeframe; other storage technologies, such as pumped hydro energy storage and compressed air energy storage, are better suited to offering flexibility in the time frame of hours to days (Miller et al. 2013). Several thermal storage technologies also can provide flexibility, such as end-use thermal storage, which can shift demand for heating and cooling, or concentrating solar power, which can use highly efficient thermal storage and become a dispatchable resource with high capacity value (Denholm et al. 2014). Many available storage technologies have a higher capital cost relative to other options for flexibility currently available. In most power systems, further technology improvements will be needed for storage to be cost competitive with other flexibility options.

Flexible conventional generation: Conventional power plants and dispatchable, non-variable RE generators such as biomass or geothermal plants provide flexibility if they have the ability to rapidly ramp-up and ramp-down output to follow net load; quickly shut-down and start-up; and operate efficiently at a lower minimum level during high RE output periods (IEA 2014). New and retrofitted large-scale power plants, as well as smaller-scale distributed generation (e.g., micro combined heat and power units), can supply flexible generation (Holttinen 2013). Examples of flexible thermal generation include aeroderivative turbines and reciprocating engines, as well as older power plants that are operated flexibly, such as coal plants in Germany.

Flexibility comes with an incremental cost for conventional thermal generators that were not designed to cycle frequently, such as older coal plants.[6] Cycling damages these plants and reduces their life expectancy, but associated costs can be reduced with strategic modifications, proactive inspections and training programs, and other types of maintenance (Cochran, Lew, and Kumar 2013). The second phase of the Western Wind and Solar Integration Study (WWSIS-2) directly addressed the impacts of high wind and solar penetration levels on thermal plant cycling. For a 33% RE scenario, WWSIS-2 concluded that from a system perspective, annual increases in cycling costs ($35 million to $157 million) are small compared to overall reductions in operational costs ($7 billion) due to avoided fuel costs (Lew et al. 2013).[7] Although there have been questions about the potential for emissions to increase in systems with high RE due to plant cycling, WWSIS-2 also concluded that 98-99% of the benefit of reductions in emissions due to generating electricity from wind and solar is maintained; increases in emissions due to added cycling reduces the emissions savings by 1-2% (Lew et al. 2013). Cycling-related costs may pose additional challenges to revenue adequacy in competitive wholesale markets.

Flexible variable RE: Technology advancements now enable wind plants to provide the full spectrum of balancing services (synthetic inertial control, primary frequency control, and automatic generation control), an increasingly common requirement for systems with high levels of RE generation (Ela et al. 2014). For example, ERCOT requires wind turbines to provide an autonomous response to changes in power grid frequency, and the Colorado utility Xcel Energy requires many turbines to be on automatic generation control, which allows the computerized control system to directly control wind generation output (Bird, Cochran, and Wang 2014). PV plants are also starting to implement similar grid requirements (Morjaria et al. 2014).

Modern turbines and solar plants can also provide voltage support. Distributed solar PV systems can be configured with smart inverters that monitor local grid conditions and autonomously provide system grid services. The California Public Utility Commission, for example, is updating interconnection requirements for distributed PV to include smart inverters that provide local voltage support, meet ramp rate requirements after an outage, and ride through frequency and voltage events (CPUC 2014).

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[6] Cycling includes the range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down, and operating at part-load (less than full output).
[7] Costs are also relatively small from a single generator perspective—typical operating costs, including fuel, are $20-$40/MWh, whereas increased operations and maintenance costs due to RE-induced cycling were $0.5-$1.3/MWh. Nevertheless, these costs can be significant from a generator perspective if profit margins are tight.

Revising grid codes early allows hardware and procurement agreements to be designed in advance of high variable RE penetration levels and reduces the financial burden associated with implementing such requirements retroactively. Germany's requirements for installed solar photovoltaic (PV) to provide grid services were applied retroactively, at considerable cost (Cochran et al. 2012).

Interconnected transmission networks: Transmission capacity is often considered an integral part of system flexibility as it offers an alternative to using variable RE generation only locally. Transmission capacity allows variable RE to instead be transmitted to other regions where the energy can be used. In addition, improving connections with neighboring transmission networks, including extending existing lines, provides the power system greater access to a range of balancing resources (Cochran et al. 2012; IEA 2014; Porter et al. 2012). The aggregation of all generation assets through such interconnection both improves flexibility and reduces net variability across the power system. Weather patterns become less correlated over larger areas, smoothing the output of wind and solar plants (Bird, Milligan, and Lew 2013). Enlarging balancing areas also lowers the net variability and uncertainty of load and variable RE.

2.2.3 Evaluate Integration Options

The appropriate combination of flexibility options for a given power system will be specific to that system and depends on the relative economics of the options available (see Figure 2), among other factors. Through a grid integration study, planners can evaluate relative costs and benefits for different options (e.g., improvements to forecasting, financial signals to incentivize fast response) by systematically testing and evaluating various combinations of new operational practices and other sources of flexibility.

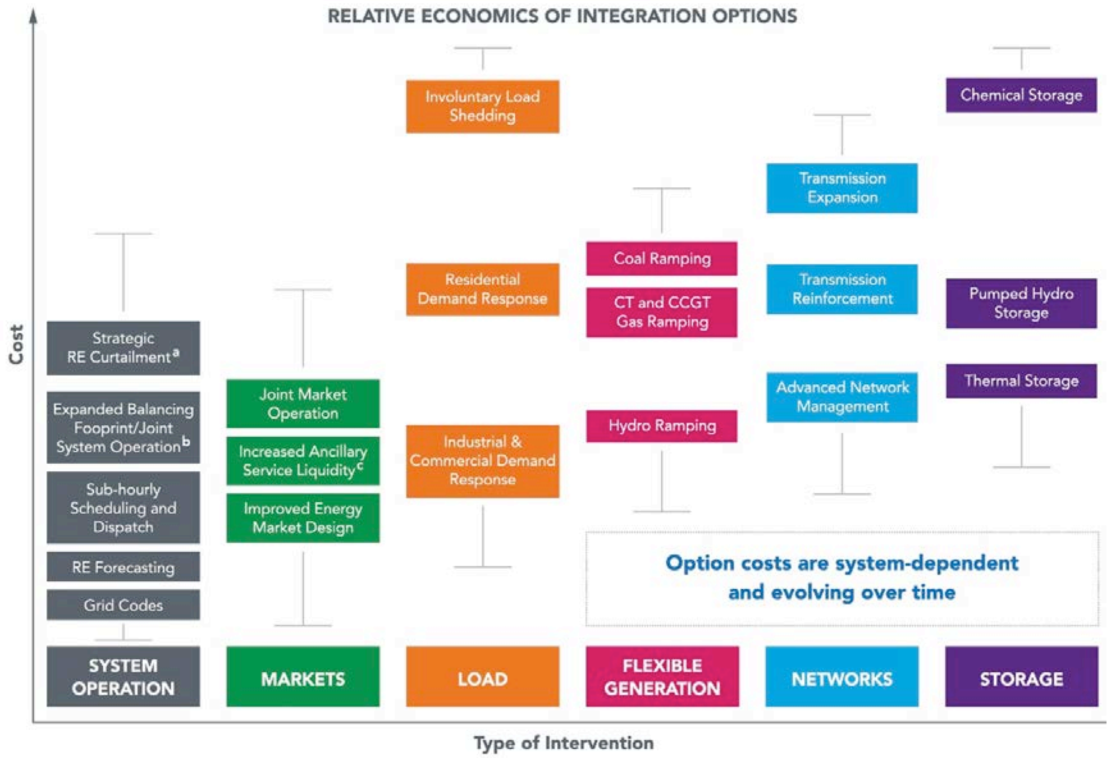

Figure 2. Types and relative economics of integration options

Note: Relative costs are illustrative, as actual costs are system-dependent. In general, changing system operation and market designs are low capital-cost options, but may require significant changes to the institutional context (Cochran et al. 2014).
a. There is a tradeoff between costs of flexibility and benefits of reduced (or no) curtailment, hence a certain level of curtailment may be a sign that the system has an economically optimal amount of flexibility.
b. Joint system operation typically involves a level of reserve sharing and dispatch co-optimization but stops short of joint market operation or a formal system merger.
c. Wind power can increase the liquidity of ancillary services and provide generation-side flexibility. Curtailed energy is also used to provide frequency response in many systems, for example Xcel Energy, EirGrid, Energinet.dk.

By adopting many of these integration best practices, utilities in many regions have successfully incorporated large amounts of variable RE. Annual energy penetrations of wind in the United States have exceeded 20% of total generation in two states (South Dakota and Iowa), while instantaneous penetration in the Xcel service territory in Colorado has exceeded 60% several times without compromising reliability (Xcel Energy 2015).

3 The Carrying Capacity of the U.S. Power Grid to Incorporate Variable RE

3.1 The Concept of Economic Carrying Capacity

Given the challenges and required changes to power system operations to incorporate high levels of variable RE, a natural follow-up question is "How much variable RE can an existing power system handle?" We use this question to frame the concept of carrying capacity of a power grid to incorporate variable RE. No single metric can measure carrying capacity, but it can be approximated both technically and economically.

Technically, carrying capacity is the point at which the addition of variable RE produces a system that cannot reliably be operated due to technical challenges or, more simply stated, the point at which the addition of variable RE breaks the grid. An example would be the point at which there is insufficient inertia in the system to recover from normal faults (Ela et al. 2014).[8] However, regional grid integration studies conducted to date have indicated that there is nearly always a technological fix that can be adopted at some cost (e.g., a change in operation or piece of hardware that can be added to the grid). So, simply deploying extremely large amounts of transmission and storage (or some other set of technologies), and modifying the RE generation to maintain system operational parameters could enable 100% penetration of wind and solar. As such, carrying capacity defined exclusively on technical factors is of limited practical value.

Because mitigation strategies that can address challenges to the integration of variable RE have associated costs and benefits, we use the term *economic* carrying capacity to represent the economically desirable limit associated with adding variable RE to any existing power system. One approach to estimating this limit is to determine the penetration of variable RE (fraction of a system's energy met by variable RE) at which the costs outweigh the benefits and additional variable RE is no longer economically desirable. The economic carrying capacity could be evaluated for a static grid, such as today's transmission configuration and operational practices, as well as under a variety of potential future conditions to consider the incremental costs and benefits associated with increasing the carrying capacity.

A critical step to effectively employ this framework is to determine the specific types of benefits to include in the benefit-to-cost ratio, such as the value of avoided fuel, avoided capacity additions, avoided emissions, and reduced fuel price volatility. While suggesting a particular set of benefits is beyond the scope of this report, the economic carrying capacity is nonetheless a useful framework with which to consider the integration challenges of variable RE and how the evolution of the grid and grid flexibility can mitigate these challenges.

3.2 Estimating the Economic Carrying Capacity of the U.S. Power Grid

Economic carrying capacity is an emergent concept, and as such has not been calculated for any specific grid. Challenges to calculating the economic carrying capacity include lack of consensus on the components of a cost-benefit ratio, and the complexity of valuing many of these cost and benefit components. These valuations require detailed grid modeling of both the generation and transmission system. Additional benefits such as the value of fuel diversity, local economic benefits, air quality, and others may be even more difficult to estimate.

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[8] These challenges include the lack of real inertia and primary frequency response from inverter-based wind and PV systems. Available technologies, including active power controls from wind, can act to mitigate these concerns but have yet to be deployed at large scale.

Nevertheless, results from power grid simulations, which simulate the operation of the power grid with increased generation from variable RE, offer some indication of economic carrying capacity of future power grids. Grid integration studies typically simulate a limited set of variable RE generation scenarios, along with grid conditions that exist in the present or may exist in some future year. These studies evaluate the operation of individual generators that respond to net system variability as well as the ability of the transmission system to accommodate additional power flows that might occur with the introduction or increase of variable RE. Many studies have identified a decrease in the value of variable RE as it begins to represent a larger percentage of an electric grid, particularly in systems that are unable to increase system flexibility (as discussed in Section 2). Decreases in value result from reduced capacity value (due to the shift in net load) and reduced energy value (due to merit order effect and/or curtailment from insufficient system flexibility or transmission). The value of other generation sources falls as well as a function of increases in their penetration, but the drop is typically less pronounced.[9]

A detailed grid integration study can explore how increasing system flexibility, including adding transmission capacity, can maintain value for variable RE as its generation increases. The importance of overall system flexibility to respond to variable RE is illustrated in Figure 3, which provides the results of a grid simulation of the western United States. This scenario, one of several assessed in WWSIS-2, evaluates the impacts of obtaining 33% of the Western Interconnection's generation from wind and solar. This particular illustration is a dispatch stack for a one-week period from the simulation of the high-solar scenario (15% contribution from solar PV, 10% solar CSP with storage, and an 8% contribution from wind). This week is a particularly challenging one from an integration standpoint, as it features a very low net load, typical in the spring, and significant thermal plant cycling.

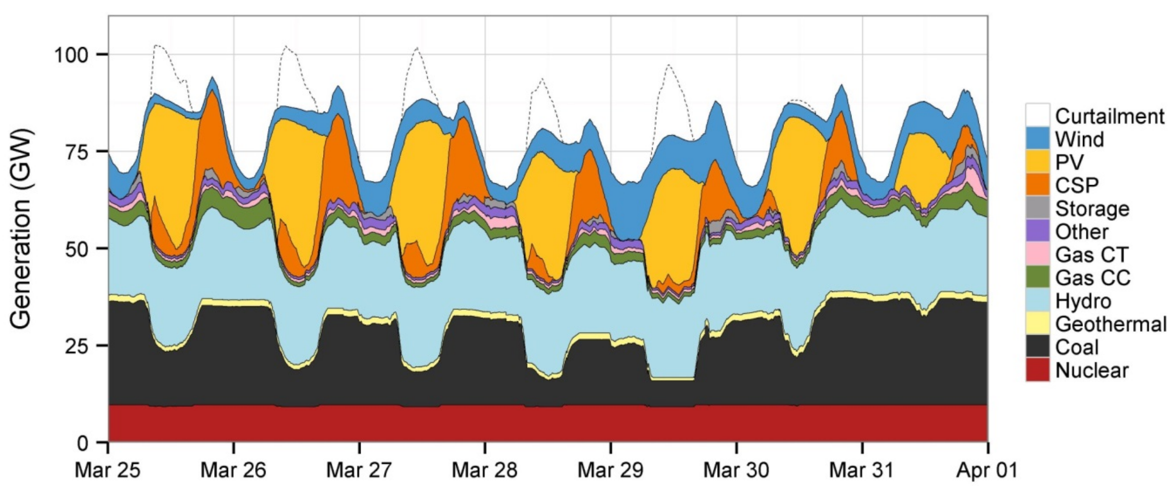

Figure 3. Simulated impacts of obtaining 33% energy from wind and solar
Source: Lew et al. 2013

During the first five days of this week, the system, which relies on a large number of coal-fired power plants, encounters flexibility constraints due to minimum generation levels of the thermal fleet. Flexibility

[9] For example, the capacity value of PV falls significantly as a function of penetration because the normal U.S. peak load, which typically occurs in the late afternoon, is met by PV; the new net load is effectively shifted later, to the early evening, when PV output has dropped substantially. Because the output of a conventional thermal plant is independent of time of day, the plant can maintain high capacity value. For additional discussion of the value of RE as a function of penetration, see Mills and Wiser 2012.

is also potentially limited by the need to run conventional generators to provide reserves to address forecast errors and provide active power control. In combination, these factors create a minimum percentage of energy that must be provided by conventional generation, which in turn results in curtailment of solar generation.

The consequence of curtailment is decreased value of the variable RE generation, as 1 MWh of variable RE displaces less than 1 MWh of thermal generation. Alternatively, curtailment can manifest in increased generation cost, as the decreased variable RE capacity factor results in an increased levelized cost of energy (LCOE) from the plant.[10] Because of the impacts of curtailment on RE value, many grid integration studies use curtailment as an important metric of system performance. Curtailment can occur due to either transmission constraints or limits on other sources of system flexibility. Many grid integration studies therefore add transmission or make changes to system flexibility to keep curtailment rates under a particular threshold.

Results from grid integration studies can provide an indication of economic carrying capacity. The key difference between a grid integration study and an economic carrying capacity study is that many grid integration studies select an RE penetration level (e.g., 30%), and evaluate the actions necessary to maintain value for variable RE at the target penetration level. The studies do not directly evaluate the cost-benefit threshold of RE penetration for those same actions, which could be higher or lower than the targeted RE level, depending on the components of the cost-benefit analysis. Therefore, we use the results of the grid integration studies to infer what actions are necessary to achieve an economic carrying capacity of a target RE penetration level.

Table 2 summarizes curtailment estimates for a number of recent integration studies that have evaluated variable RE generation at levels of at least 30% of total system generation: WWSIS-2, a PJM wind integration study, a 2011 study on wind integration in the Eastern Interconnect (EWITS), and two recent studies of California.[11] These studies use different methods and models, so their results are not directly comparable; however, they share several common themes. First, all show the importance of additional transmission capacity to integrating increasing amounts of variable RE and imply that the current carrying capacity of the grid is likely limited by existing transmission capacity, especially in scenarios of significant wind development.

[10] The LCOE from a wind or solar plant is equal to the annual carrying cost divided by annual energy sold. As the curtailment rate increases, the annual energy sold decreases, which results in a relative cost equal to the base cost divided by (1 – curtailment rate).
[11] These studies primarily explore the impact of variable RE generation on the bulk transmission system, and do not consider the impacts on or the carrying capacity of the distribution network.

Table 2. Estimates of Transmission-related Curtailment of Variable RE in Recent U.S. Integration Studies

Study	RE Penetration	Curtailment
PJM (GE Energy 2014)	Up to 30%	1.5-3% with new transmission.
Western United States (WWSIS-2) (Lew et al. 2013)	33%	10% without new transmission, 1.5% with new transmission (High Wind Scenario). Curtailment with transmission in other scenarios as high as 5%.
California (CAISO 2011)	33%	<1%, Relies in part on flexibility from surrounding regions.
California (E3 2014)	33-50%	0.2% in 33% scenario, 1.8% in 40% scenario, and 8.9% in 50% high solar scenario. Also evaluates marginal curtailment rates and mitigation options. Mitigation options reduce curtailment rates by 50% or more.
Eastern United States (EWITS) (Corbus et al. 2011)	Up to 30%	19%-48% without new transmission depending on scenario. With transmission 1%-7% in 20% scenario and 3-10% in 30% scenario.

These studies also suggest that relatively low curtailment rates are possible with the addition of sufficient transmission, with both WWSIS-2 and EWITS comparing curtailment with and without additional transmission. Table 3 summarizes the transmission addition in three grid integration studies.[12] Transmission is needed not only to increase system flexibility, but to enable access to new sources of wind generation. Evaluating the transmission system is complicated because of the need to consider multiple aspects of transmission availability. This includes direct transmission access (the ability of wind to access the transmission network) and the ability of the system to transmit energy over large areas to take advantage of the spatial diversity of wind and solar resources, loads, and generator flexibility.

The specific approach used to evaluate additional transmission needs varies by study. For example in WWSIS-2, the study incrementally adds transmission across zonal interfaces where the price of energy typically exceeds a threshold value of $10/MWh, based on comparing the net benefit of additional transmission to the estimated transmission costs of about $1,600/MW-mile for 250 miles of new transmission with an 11% fixed-charge rate.[13] Similarly, the EWITS study (Corbus et al. 2011) estimates new transmission capacity requirements by comparing estimated costs to benefits of congestion relief. Table 3 includes an estimated cost of this new transmission, with a uniform comparison provided in the last column in terms of cost per MWh of variable RE (using a fixed charge rate of 11% in all cases).

[12] These studies do not typically differentiate between transmission capacity developed for wind and for solar. Also, many challenges associated with new transmission, including permitting, siting, and cross-jurisdictional coordination, are not considered in grid integration studies.
[13] The fixed charge rate is defined as the amount of revenue per dollar of investment that must be collected annually from customers to pay the carrying charges on that investment.

Table 3. Evaluations of Transmission Costs in Recent U.S. Integration Studies

Study	RE Penetration	Variable RE Added (GW)	Total Transmission Added	Total Additional Transmission Costs ($B)	Transmission Cost per unit RE energy ($/MWh)[a]
PJM (GE Energy 2014)	30%	102-114	1,000- 3,000 miles	5.0-13.7	2.1-5.9
WWSIS-2 (Lew et al. 2013)	33%	90-107	10,500-16,500 MW zonal transfer capacity	3.6-5.3	1.5-2.2
EWITS (Corbus et al. 2011)	30%	338	23,000 miles	92.5	9.1

[a] Fixed charge rate of 11% applied in all scenarios

In addition to new transmission, these studies also assume several other changes to the grid, primarily in how the system is operated in high variable RE scenarios. For example, a significant assumption in the WWSIS-2 study is larger balancing areas than currently adopted, effectively allowing greater sharing of resources via frictionless exchange of energy across most of the Western Interconnection. This assumption enables substantial benefits from spatial diversity of both generation and load, including reduced variability, but would require new markets or policies to actually implement. In contrast the Eastern Interconnection contains several large ISOs/RTOs, which already enable efficient exchange of energy over large geographic boundaries—this market structure has been instrumental in enabling high wind penetration levels in several Midwestern states (FERC 2011).

Overall, studies to date imply that an economic carrying capacity of 30% in much of the United States will require largely understood changes to operational practices as well as transmission capacity expansion. However, further analysis is needed to establish more detailed regional carrying capacities across the United States, particularly at penetrations above 30%. This is particularly important as preliminary studies indicate that marginal or incremental curtailment rates can increase dramatically at penetrations beyond 30% without more substantial measures to increase grid flexibility. Economic carrying capacity is not a fixed value and can (and will) change as the power grid evolves. A thorough examination of regional carrying costs requires detailed analysis that considers the variable RE mix, power grid configuration, transmission expansion availability and costs, fuel cost, and operational practices, among other factors.

4 Conclusion

Operators of power systems throughout the United States have already integrated significant levels of variable RE generation while maintaining reliability. All power systems have an inherent level of flexibility, designed to accommodate variable and uncertain load and contingencies related to network and conventional power plant outages. Because of this existing flexibility, power system operators have accommodated increased variable RE largely without substantial new investment in system flexibility, such as new storage, demand response, or generation dedicated to addressing RE variability and uncertainty.

To achieve higher penetration levels, multiple grid integration studies in the United States have evaluated scenarios where an economic carrying capacity of at least 30% is achieved by implementing largely well-understood changes to system operations along with transmission capacity expansion. Specific transmission requirements have depended on the type of added generation (e.g., wind, utility-scale or distributed PV).

Still higher levels of, variable RE generation is technically feasible but could test the economic carrying capacity of the U.S. power grid. High RE penetrations could significantly change dispatch requirements and use of conventional generators, requiring a reassessment of market mechanisms to ensure revenue sufficiency. System-specific analyses can be conducted to identify the combination of technologies, grid infrastructure, and market and operational changes that will increase the carrying capacity of the power grid to exceed 30% of variable RE.

In the United States and internationally, grid integration issues—and potential solutions—are coming into focus through real-world experience and sophisticated research and analysis. The concept of economic carrying capacity provides an organizing framework in which meaningful grid integration analysis can be designed. Equally importantly, this framework provides a basis for tailoring such analysis to region-specific considerations. Understanding that carrying capacity is not fixed, but could be improved through technical and institutional changes, creates the opportunity to enable levels of RE generation beyond 30% through strategic investments in both demand- and supply-side sources of flexibility.

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Appendix: Renewable Electricity Market Status

RE systems, including hydro, wind, biomass, geothermal, and solar, generated 515 terawatt hours of electricity in the United States in 2013, equivalent to 13.1% of total U.S. electricity generation (Esterly 2014). Of this, variable RE generation—wind and solar—contributed 4.6% of annual U.S. electricity generation. Table A-1 documents the capacity, capacity growth, generation, and top U.S. state markets for RE sources in 2013. The largest installed capacities are hydropower (78 GW) and wind (61 GW[14]), but the fastest growth technologies were PV (12 GW) and concentrated solar power (CSP) (1 GW) markets (Esterly 2014). California leads U.S. states in terms of total installed RE capacity, ranking first for solar PV, solar CSP, geothermal, and biomass (Esterly 2014). Texas is the leading wind producer, and Washington remains first in hydropower production. Expansion of the U.S. renewables market has been driven primarily by reduced generation costs, federal tax incentives, and state-level renewable portfolio standards (IEA 2013b; McCrone et al. 2014).[15]

Table A-1. 2013 U.S. Installed Capacity and Generation for Renewable Energy Technologies

Technology	Cumulative Capacity (GW)	2013 Additional Capacity (GW)	Capacity Growth from 2012	Electricity Generation (GWh) and (Share of Total U.S. Generation)	Top Five States by Installed Cumulative Capacity,
Hydro	78.5	0.2	0%	269,137 (6.6%)	Washington, California, Oregon, New York, Alabama
Wind[a]	61.1	1.1	2%	167,663 (4.1%)	Texas, California, Iowa, Illinois, Oregon
Biomass	14.7	0.7	5%	59,894 (1.5%)	California, Florida, Virginia, Georgia, Alabama
Solar PV[a]	12.1	4.7	64%	21,074 (0.5%)	California, Arizona, New Jersey, North Carolina, Massachusetts
Solar CSP[a]	0.9	0.4	80%		California, Arizona, Florida, Nevada, Hawaii
Geothermal	3.8	0.4	12%	16,518 (0.4%)	California, Nevada, Utah, Hawaii, Oregon
Total RE	171.1	7.5	5%	534,286 (13.1%)	California, Washington, Texas, Oregon, Iowa

[a]Wind, solar PV, and solar CSP (when deployed without thermal storage) constitute variable RE technologies. Solar PV includes grid-connected centralized and distributed PV, but not off-grid PV.
Source: Esterly 2014

[14] Including Puerto Rico's installed wind capacity.

[15] For example, new wind capacity additions totaled 1,087 MW in 2013, a large decrease from the 13,089 MW installed in 2012. This drop can be attributed largely to a late extension of and modified eligibility requirements for the federal production tax credit (PTC) (Wiser and Bolinger 2014). Based on projections of projects under construction, greater incremental increases in wind capacity are expected for 2014 and 2015 as compared to 2013, but are not anticipated to exceed the 2012 additions (Shurey 2014).

United States in the Context of the Global Renewable Electricity Market

Global RE power capacity grew to 1,560 GW in 2013, equivalent to 27% of the world's total installed electricity capacity, including 8% from variable RE technologies (Esterly 2014). Worldwide, the highest capacity growth from 2012 occurred in the solar PV (39%), solar CSP (36%), and wind markets (12%). Table A-2 presents information equivalent to that in Table A-1 but at a global scale. The United States ranks in the top five countries in terms of installed capacity in each of the major commercialized RE technologies. China, the United States, Brazil, Canada, and Germany have the most installed renewable electricity capacity.

RE generation also meets increasingly high percentages of annual demand, including in the countries of Denmark (33.2% from wind), Spain (20.9% from wind), and Italy (7.8% solar PV) (REN21 2014). Instantaneous RE penetration levels – the percentage of electricity supplied from RE at any given time – have reached over 90% in Denmark and Portugal (Novas Energias 2011), and over 60% in Spain (Sills 2012) and Colorado (Goggin 2013). The island grids of Ireland and Hawaii have also experienced high levels of instantaneous renewable energy penetration, with incidents of 50% and 60.7% respectively (EirGrid 2013; Hawaiian Electric et al. 2014). These levels are especially significant given that the two power systems do not have access to large interconnections with which they can balance variability.

Table A-2. 2013 Global Installed Capacity and Generation for Renewable Energy Technologies

Technology	Cumulative Capacity (GW)	2013 Additional Capacity (GW)	Capacity Growth over Previous Year	Generation (GWh) and (Share of Total Global Generation)	Top Five Countries by Installed Capacity (for grid-tied systems)
Wind[a]	318.0	35.0	12%	835,704 (3.7%)	China, United States, Germany, Spain, India
Solar PV[a]	139.0	39.0	39%	177,916 (0.8%)	Germany, China, Italy, Japan, United States
Solar CSP[a]	3.4	0.9	36%		Spain, United States, United Arab Emirates, India, Algeria
Geothermal	12.0	0.5	3%	73,584 (0.3%)	United States, Philippines, Indonesia, Mexico, Italy
Biomass	88.0	5.0	6%	416,275 (1.8%)	United States, Germany, China, Brazil, India
Hydro	1,000.0	40.0	1%	3,591,600 (15.9%)	China, Brazil, United States, Canada, Russia
Total RE	1,560.0	120.4	6%	5,095,079 (22.6%)	China, United States, Brazil, Canada, Germany

[a]Wind, solar PV, and solar CSP (when deployed without thermal storage) constitute variable RE technologies.
Source: REN21 2014

Despite significant increases in installed capacity in 2013, global investments in new RE electricity generation and fuel production capacity decreased by 23% from the 2011 high of US$279 billion and by

14% from 2012, settling at $214 billion in 2013 (REN21 2014; McCrone et al. 2014).[16] By comparison, $36 billion was invested in 2013 in the United States (McCrone 2014).

Reduced investment may be due to several factors, including flat or decreasing growth in electricity demand, decreased RE capital costs, and policy uncertainty. Annual U.S. electricity generation declined from a high in 2007 of 4.2 trillion kWh to 4.1 trillion kWh in 2013 (EIA 2014c). RE capital costs have dropped as well—from Q1 of 2010 through Q1 of 2014, the levelized costs of energy for crystalline silicon PV and onshore wind have fallen by 53% and 15%, respectively (McCrone et al. 2014).

Despite reduced capital and generation costs, a key driver of RE deployment is government policy incentives (REN21 2014). Targets, feed-in tariffs, tenders, and tax incentives are offered in over 100 countries, although the recent drop in costs may provide room for governments to lower financial incentives (IEA 2013b).[17] However, recent sudden and extreme policy changes have created perceptions of additional investment risk and subsequent market booms and busts, most notably in the solar PV and onshore wind markets (IEA 2014).

Manufacturing

Globally, the manufacturing of renewable energy equipment has grown significantly over the past 10 years, with new annual investment increasing from US$600 million in 2004 to $12.5 billion in 2013 (REN 21 2014). Sixty-four percent of solar modules are produced in China, followed by the rest of Asia (16%), Europe (9%), Japan (6%), and the United States (2%) (Esterly 2014).[18] China, Denmark, Germany, India, Spain, and the United States lead in wind turbine manufacturing (REN21 2014).

As with other industries, decisions on where to manufacture RE components are driven by several factors, including market and policy considerations, learning effects such as economy-of-scale benefits, the ease of doing business, and regulatory contexts (Porter 1990). In some instances, developers have been drawn to regions with low-cost financing, and may choose locations that minimize specific business risks, such as exchange rate risks, trade fees and barriers, and shipping costs (IEA 2013b). High levels of competition among manufacturers, policy changes, and dynamic market conditions are driving consolidation among solar PV and wind manufacturers in select regions (IEA 2013b).

Technology Cost and Performance Characterizations

Table A-3 summarizes renewable electricity system cost and performance characterizations for the United States, as determined by the Energy Information Administration (EIA) and Bloomberg New Energy Finance (BNEF), in terms of typical capacity factor, cost, and lifespan. LCOEs are project-specific and are highly dependent on climate and location, among other factors. Nevertheless, based on national averages, EIA’s 2014 Annual Energy Outlook Reference Case projects that the LCOE for wind will be cost-competitive with new coal and nuclear ($100/MWh) as well as natural gas ($70/MWh) by 2019 (EIA 2014b). Other projections, including those by BNEF, indicate even lower LCOEs by 2019, with solar PV potentially also competitive with coal and nuclear. Even for those plants that are not cost-competitive,

[16] Bloomberg New Energy Finance (BNEF) investment data includes biomass, geothermal, wind, and hydropower projects over 1 MW; all ocean energy; all biofuels over 1 million liters; and all solar with small-scale projects (less than 1 MW) estimated separately (REN21 2014). Investments are reported in nominal dollars.
[17] A feed-in tariff is a production-based incentive for renewable energy often coupled with additional supportive policies, such as priority access to the power grid. A tender is a public competitive bidding process whereby independent power producers make offers to supply certain amounts and types of energy at a specific price to a utility or power system operator.
[18] Modules are one of many components in the PV supply chain.

long-term, unsubsidized power purchase agreements for wind or solar can be a hedge against future fuel prices (IEA 2013a).[19]

Table A-3. Technology Characterizations

	Approximate Typical Capacity Factor[20]	Expected LCOE in 2019 ($/MWh)	Economic Lifespan (years)
Wind[a]	35%	$37 - $81	24
Solar PV[a] (Utility Scale)	25%	$72 to $86	20 - 30
Solar CSP[a]	20% to 56%	$118[21] to $130 (with storage)	20 - 30
Geothermal[a]	92%	$89 to $142	25 - 30
Biomass	83%	$87 to $116	20
Hydropower	53%	$85	40 - 80

[a]Wind, solar PV, and solar CSP (when deployed without thermal storage) constitute variable RE technologies. Geothermal characterization applies to conventional hydrothermal resources.
Sources: Capacity factors and hydropower LCOE estimate: EIA 2014b; Other LCOE estimates: Lazard 2014; Lifespan: IPCC 2011.

Projections of Future Renewable Electricity Deployment

According to the EIA's 2014 Annual Energy Outlook Reference Case, between 2013 and 2017, installed RE capacity in the United States is expected to have a five-year compound annual growth rate (CAGR) in a range of 0.82% to 3.50% (EIA 2014c), assuming existing incentives and associated expirations in current law. A high rate of growth in installed capacity is projected for solar PV in the near term, with moderate rates of growth in solar CSP, and wind. No offshore wind deployment is anticipated in the United States in the near term, and projections exclude emerging technologies (EIA 2014c).[22] Looking further into the future, from 2018 through 2022, the EIA scenarios estimate a significantly decreased rate of growth with approximately 1% annual growth for all technologies.[23] Other organizations, such as BNEF offer alternative projections. BNEF anticipates a five-year CAGR of 8.28% between 2013 and 2017 for new wind capacity, assuming no extension of the production tax credit and with continued implementation of current state renewable portfolio standards (BNEF 2013).[24]

Although not modeled in the EIA projections, EPA's Clean Power Plan proposal could result in states implementing additional policies to meet state-level carbon emissions targets (EPA 2014). It is unclear

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[19] See Blair (forthcoming) for another set of cost and performance assumptions that will inform NREL's electric sector analysis conducted in 2015, http://www.nrel.gov/analysis/data_tech_baseline.html.
[20] The capacity factors included within this table are typical and not system-specific. Power grid operators have likely defined their own capacity factor estimates for aggregated systems over time, which may differ from the capacity factors included here.
[21] The estimated $130 LCOE for solar CSP is for a molten salt power tower, in real $2010 and with a capacity factor of 56% (10 hours of thermal energy storage) (DOE 2014).
[22] These emerging technologies include Engineered Geothermal Systems (EGS) and a variety of ocean technologies.
[23] For details on the EIA projection assumptions, see Appendix E of the 2014 AEO Report: http://www.eia.gov/forecasts/aeo/pdf/0383%282014%29.pdf.
[24] See Blair (forthcoming) for another set of deployment projections based on a range of assumption scenarios and using NREL's electric sector capacity expansion and dispatch model, the Regional Energy Deployment Systems (ReEDS).

what impact this plan will have on renewables markets, if and when implemented, both because the plan may change significantly before it is finalized and because states have many ways to meet these targets. For example, states could improve coal plant efficiency, use combined cycle gas, operate existing nuclear plants, and increase energy efficiency and/or RE to meet carbon emissions goals.

Global renewable electricity capacity is projected to grow significantly over the next five years (IEA 2013a), including double-digit CAGRs in offshore wind, solar CSP, and solar PV (IEA 2013a), as illustrated in Table A-4.

Table A-4. Projected Global RE Capacity by Technology, from 2013 – 2017 (GW)

		2013	2014	2015	2016	2017	5-Year CAGR
Commercialized Technologies	Wind - onshore[a]	313	357	399	442	486	9.2%
	Solar PV[a]	128	161	194	230	268	15.9%
	Solar CSP[a]	4	6	7	8	10	20.1%
	Geothermal	12	12	13	14	14	3.1%
	Hydropower	1,138	1,173	1,209	1,249	1,291	2.6%
Emerging Technologies	Wind - offshore[a]	8	11	14	17	22	22.4%
	Ocean	1	1	1	1	1	0.0%
Total RE		**1,693**[25]	**1,815**	**1,941**	**2,073**	**2,211**	**5.5%**

[a] Onshore wind, offshore wind, solar PV, and solar CSP (when deployed without thermal storage) constitute variable RE technologies.
Source: IEA 2013a

[25] Note the IEA reported and projected renewable electricity capacity numbers include both on- and off-grid systems. Also, IEA's reported installed capacity for 2013 differs from the REN21 Renewable Energy Global Status Report estimate of 1,560 GW installed as of 2013. See Table A-2.