NATIONAL RENEWABLE ENERGY LABORATORY

Renewable Electricity Futures Study

Executive Summary

Volume 1 PDF

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Renewable Electricity Futures Study

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Renewable Electricity Futures Study

Executive Summary

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Perspective

The Renewable Electricity Futures Study (RE Futures) provides an analysis of the grid integration opportunities, challenges, and implications of high levels of renewable electricity generation for the U.S. electric system. The study is not a market or policy assessment. Rather, RE Futures examines renewable energy resources and many technical issues related to the operability of the U.S. electricity grid, and provides initial answers to important questions about the integration of high penetrations of renewable electricity technologies from a national perspective. RE Futures results indicate that a future U.S. electricity system that is largely powered by renewable sources is possible and that further work is warranted to investigate this clean generation pathway. The central conclusion of the analysis is that renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the United States.

The renewable technologies explored in this study are components of a diverse set of clean energy solutions that also includes nuclear, efficient natural gas, clean coal, and energy efficiency. Understanding all of these technology pathways and their potential contributions to the future U.S. electric power system can inform the development of integrated portfolio scenarios. RE Futures focuses on the extent to which U.S. electricity needs can be supplied by renewable energy sources, including biomass, geothermal, hydropower, solar, and wind.

The study explores grid integration issues using models with unprecedented geographic and time resolution for the contiguous United States. The analysis (1) assesses a variety of scenarios with prescribed levels of renewable electricity generation in 2050, from 30% to 90%, with a focus on 80% (with nearly 50% from variable wind and solar photovoltaic generation); (2) identifies the characteristics of a U.S. electricity system that would be needed to accommodate such levels; and (3) describes some of the associated challenges and implications of realizing such a future. In addition to the central conclusion noted above, RE Futures finds that increased electric system flexibility, needed to enable electricity supply-demand balance with high levels of renewable generation, can come from a portfolio of supply- and demand-side options, including flexible conventional generation, grid storage, new transmission, more responsive loads, and changes in power system operations. The analysis also finds that the abundance and diversity of U.S. renewable energy resources can support multiple combinations of renewable technologies that result in deep reductions in electric sector greenhouse gas emissions and water use. The study finds that the direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Of the sensitivities examined, improvement in the cost and performance of renewable technologies is the most impactful lever for reducing this incremental cost. Assumptions reflecting the extent of this improvement are based on incremental or evolutionary improvements to currently commercial technologies and do not reflect U.S. Department of Energy activities to further lower renewable technology costs so that they achieve parity with conventional technologies.

RE Futures is an initial analysis of scenarios for high levels of renewable electricity in the United States; additional research is needed to comprehensively investigate other facets of high renewable or other clean energy futures in the U.S. power system. First, this study focuses on renewable-specific technology pathways and does not explore the full portfolio of clean technologies that could contribute to future electricity supply. Second, the analysis does not attempt a full reliability analysis of the power system that includes addressing sub-hourly, transient, and distribution system requirements. Third, although RE Futures describes the system characteristics needed to accommodate high levels of renewable generation, it does not address the institutional, market, and regulatory changes that may be needed to facilitate such a transformation. Fourth, a full cost-benefit analysis was not conducted to comprehensively evaluate the relative impacts of renewable and non-renewable electricity generation options.

Lastly, as a long-term analysis, uncertainties associated with assumptions and data, along with limitations of the modeling capabilities, contribute to significant uncertainty in the implications reported. Most of the scenario assessment was conducted in 2010 with assumptions concerning technology cost and performance and fossil energy prices generally based on data available in 2009 and early 2010. Significant changes in electricity and related markets have already occurred since the analysis was conducted, and the implications of these changes may not have been fully reflected in the study assumptions and results. For example, both the rapid development of domestic unconventional natural gas resources that has contributed to historically low natural gas prices, and the significant price declines for some renewable technologies (e.g., photovoltaics) since 2010, were not reflected in the study assumptions.

Nonetheless, as the most comprehensive analysis of U.S. high-penetration renewable electricity conducted to date, this study can inform broader discussion of the evolution of the electric system and electricity markets toward clean systems.

The RE Futures team was made up of experts in the fields of renewable technologies, grid integration, and end-use demand. The team included leadership from a core team with members from the National Renewable Energy Laboratory (NREL) and the Massachusetts Institute of Technology (MIT), and subject matter experts from U.S. Department of Energy (DOE) national laboratories, including NREL, Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL), as well as Black & Veatch and other utility, industry, university, public sector, and non-profit participants. Over the course of the project, an executive steering committee provided input from multiple perspectives to support study balance and objectivity.

RE Futures is documented in four volumes of a single report: Volume 1—describes the analysis approach and models, along with the key results and insights; Volume 2 describes the renewable generation and storage technologies included in the study; Volume 3 presents end-use demand and energy efficiency assumptions; and Volume 4 discusses operational and institutional challenges of integrating high levels of renewable energy into the electric grid. The Executive Summary for RE Futures is both included in Volume 1 and presented separately here.

Acknowledgments

The Project Leaders for the Renewable Electricity Futures Study gratefully acknowledge the significant contributions from the numerous individuals on the RE Futures team, more than 110 individuals from more than 35 organizations as listed in Appendix D. We appreciate their thorough and thoughtful consideration of the present state and future potential of renewable electricity generation technologies, use of electricity, and electric sector operation. This report is the culmination of their contributions. We are also grateful to the members of the study's executive steering committee, who assisted the RE Futures team in evolving and finalizing the scenarios to include and reviewed and provided comments on the analysis at various stages. We also thank the many outside individuals who reviewed the draft documents.

The ability to represent the technical aspects of future electricity generation portfolios, particularly with high levels of renewable electricity generation, requires sophisticated models operated by experienced analysts. We are grateful to Walter Short for his innovation, vision and leadership at NREL over several decades that led to development of both the Regional Energy Deployment System (ReEDS) and the strong team of analysts who use this model and other tools to provide context and insight around future electricity generation portfolios for this study and many others.

The support and guidance of management at NREL and MIT also was critical to the completion of this study. In particular, we recognize Robin Newmark and Bobi Garrett for their leadership.

We are grateful to the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy for sponsoring this work. We especially thank Sam Baldwin for his vision and leadership in conceiving, supporting, and contributing to this study from beginning to end. We also thank DOE's Office of Electricity Delivery and Energy Reliability for its input and guidance on specific aspects of the analysis, as well as valuable comments and helpful suggestions to improve the content of the report. NREL's contributions to this report were funded by the DOE Office of Energy Efficiency and Renewable Energy under contract number DE-AC36-08GO28308.

List of Acronyms and Abbreviations

AC	alternating current
BA	balancing area
Btu	British Thermal Unit(s)
CAES	compressed air energy storage
CC	combined cycle
CCS	carbon capture and storage
CO_2	carbon dioxide
CO_2e, CO_2eq	carbon dioxide equivalent
CSP	concentrating solar power
CT	combustion turbine
DC	direct current
DOE	U.S. Department of Energy
EEPS	energy efficiency portfolio standard
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EREC	European Renewable Energy Council
GHG	greenhouse gases
GWEC	Global Wind Energy Council
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
MW	megawatt(s)
MWh	megawatt-hour(s)
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RE	renewable electricity
RE Futures	Renewable Electricity Futures Study
ReEDS	Regional Energy Deployment System
RE-ETI	Renewable Electricity—Evolutionary Technology Improvement
RE-ITI	Renewable Electricity—Incremental Technology Improvement

RE-NTI	Renewable Electricity—No Technology Improvement
SNL	Sandia National Laboratories
SolarDS	Solar Deployment System
TW	terawatt(s)
TWh	terawatt-hour(s)
yr	year

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The Renewable Electricity Futures Study (RE Futures) is an initial investigation of the extent to which renewable energy supply can meet the electricity demands of the contiguous United States[1] over the next several decades. This study includes geographic and electric system operation resolution that is unprecedented for long-term studies of the U.S. electric sector. The analysis examines the implications and challenges of renewable electricity generation levels—from 30% up to 90%, with a focus on 80%, of all U.S. electricity generation from renewable technologies—in 2050. At such high levels of renewable electricity penetration, the unique characteristics of some renewable resources, specifically geographical distribution and variability and uncertainty in output, pose challenges to the operability of the U.S. electric system. The study focuses on some key technical implications of this environment, exploring whether the U.S. power system can supply electricity to meet customer demand with high levels of renewable electricity, including variable wind and solar generation. The study also begins to address the potential economic, environmental, and social implications of deploying and integrating high levels of renewable electricity in the United States.

RE Futures was framed with a few important questions:

- The United States has diverse and abundant renewable energy resources that are available to contribute higher levels of electricity generation over the next decades. Future renewable electricity generation will be driven in part by federal incentives and renewable portfolio standards mandated in many states.[2] Practically, how much can renewable energy technologies, in aggregate, contribute to future U.S. electricity supply?

- In recent years, variable renewable electricity generation capacity in the United States has increased considerably. Wind capacity, for example, has increased from 2.6 GW in 2000 to 40 GW in 2010, while solar capacity has also begun to grow rapidly. Can the U.S. electric power system accommodate higher levels of variable generation from wind or solar photovoltaics (PV)?

- Overall, renewable energy contributed about 10% of total power-sector U.S. electricity supply in 2010 (6.4% from hydropower, 2.4% from wind energy, 0.7% from biopower, 0.4% from geothermal energy, and 0.05% from solar energy).[3] Are there synergies that can be realized through combining these diverse sources, and to what extent can aggregating their output over larger areas help enable their integration into the power system?

[1] Alaska, Hawaii, and the U.S. Territories were not included in this study because they rely on electric grid systems that are not connected to the contiguous United States. However, both states and the territories have abundant renewable resources, and they have efforts are underway to substantially increase renewable electricity generation (see Volume 1, Text Box Introduction-1).
[2] Some states have targets of a 20%–30% share of total electricity generation (see http://www.dsireusa.org/ for information on specific state standards) and are making progress toward meeting these goals.
[3] These data reflect estimates for the electric power sector only, and they exclude the end use sectors (i.e., on-site electric power supply that directly meets customer demands). If the end-use and electric power sectors are considered together, the percentage contribution from biomass would increase from 0.7% to 1.4%, and the contribution from solar would increase from 0.05% to 0.12%.

Multiple international studies[4] have explored the possibility of achieving high levels of renewable electricity penetration, primarily as a greenhouse gas (GHG) mitigation measure. RE Futures presents systematic analysis of a broad range of potential renewable electricity futures for the contiguous United States based on unprecedented consideration of geographic, temporal, and electric system operation aspects.[5]

RE Futures explores a number of scenarios using a range of assumptions for generation technology improvement, electric system operational constraints, and electricity demand to project the mix of renewable technologies—including wind, PV, concentrating solar power (CSP), hydropower, geothermal, and biomass—that meet various prescribed levels of renewable generation, from 30% to 90%. Additional sensitivity cases are focused on an 80%-by-2050 scenario. At this 80% renewable generation level, variable generation from wind and solar technologies accounts for almost 50% of the total generation.

Within the limits of the tools used and scenarios assessed, hourly simulation analysis indicates that estimated U.S. electricity demand in 2050 could be met with 80% of generation from renewable electricity technologies with varying degrees of dispatchability, together with a mix of flexible conventional generation and grid storage, additions of transmission, more responsive loads, and changes in power system operations.[6] Further, these results were consistent for a wide range of assumed conditions that constrained transmission expansion, grid flexibility, and renewable resource availability. The analysis also finds that the abundance and diversity of U.S. renewable energy resources can support multiple combinations of renewable technologies that result in deep reductions in electric sector greenhouse gas emissions and water use. Further, the study finds that the incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Of the sensitivities examined, improvement in the cost and performance of renewable technologies is the most impactful level for reducing this incremental cost.

While this analysis suggests such a high renewable generation future is possible, a transformation of the electricity system would need to occur to make this future a reality. This transformation, involving every element of the grid, from system planning through operation, would need to ensure adequate planning and operating reserves, increased flexibility of the electric system, and expanded multi-state transmission infrastructure, and would likely rely on the development and adoption of technology advances, new operating procedures, evolved business models, and new market rules.

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[4] As examples, recent detailed studies include those prepared for Europe (ECF 2010) and Germany (SRU 2010), as well as a review of 164 global energy scenarios by the Intergovernmental Panel on Climate Change (IPCC 2011). Cochran et al. (2012) also describes several case studies of countries successfully managing high levels of variable renewable energy on their electric grids.

[5] Previous, more conceptual or more-limited analyses of high penetrations of renewable energy in the United States and globally include (but are not limited to) Pacala and Socolow (2004); ACORE (2007); Kutscher (2007); Greenblatt (2009); GWEC/GPI (2008); Fthenakis et al. (2009); Jacobson and Delucchi (2009); Sawin and Moomaw (2009); EREC/GPI (2008); and Lovins (2011).

[6] The study did not conduct a full reliability analysis, which would include sub-hourly, stability, and AC power flow analysis.

Key results of this study include the following:

- Deployment of Renewable Energy Technologies
  - Renewable energy resources, accessed with commercially available generation technologies, could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level.
  - All regions of the United States could contribute substantial renewable electricity supply in 2050, consistent with their local renewable resource base.
  - Multiple technology pathways exist to achieve a high renewable electricity future. Assumed constraints that limit power transmission infrastructure, grid flexibility, or the use of particular types of resources can be compensated for through the use of other resources, technologies, and approaches.
  - Annual renewable capacity additions that enable high renewable generation are consistent with current global production capacities but are significantly higher than recent U.S. annual capacity additions for the technologies considered. No insurmountable long-term constraints to renewable electricity technology manufacturing capacity, materials supply, or labor availability were identified.
- Grid Operability and Hourly Resource Adequacy
  - Electricity supply and demand can be balanced in every hour of the year in each region with nearly 80% electricity from renewable resources, including nearly 50% from variable renewable generation, according to simulations of 2050 power system operations.
  - Additional challenges to power system planning and operation would arise in a high renewable electricity future, including management of low-demand periods and curtailment of excess electricity generation.
  - Electric sector modeling shows that a more flexible system is needed to accommodate increasing levels of renewable generation. System flexibility can be increased using a broad portfolio of supply- and demand-side options, and will likely require technology advances, new operating procedures, evolved business models, and new market rules.
- Transmission Expansion
  - As renewable electricity generation increases, additional transmission infrastructure is required to deliver generation from cost-effective remote renewable resources to load centers, enable reserve sharing over greater distances, and smooth output profiles of variable resources by enabling greater geospatial diversity.
- Cost and Environmental Implications of High Renewable Electricity Futures
  - High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use.
  - The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Improvement in the cost

and performance of renewable technologies is the most impactful lever for reducing this incremental cost.

- Effects of Demand Growth
  - With higher demand growth, high levels of renewable generation present increased resource and grid integration challenges.

This report presents the analysis of some of the technical challenges and opportunities associated with high levels of renewable generation in the U.S. electric system. However, the analysis presented in this report represents only an initial set of inquiries on a national scale. Additional studies are required to more fully assess the technical, operational, reliability, economic, environmental, social, and institutional implications of high levels of renewable electricity generation, and further explore the nature of the electricity system transformation required to enable such a future.

Study Organization and Report Structure

RE Futures was led by a team from the National Renewable Energy Laboratory (NREL) and the Massachusetts Institute of Technology (MIT). The leadership team coordinated teams of subject matter experts from U.S. Department of Energy (DOE) national laboratories, including Idaho National Laboratory (INL), Lawrence Berkeley National Laboratory (LBNL), NREL, Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL), as well as Black & Veatch and other utility, industry, university, public sector, and non-profit participants. These expert teams explored the prospects for large-scale deployment of specific renewable generation and storage technologies, along with some of the issues and challenges associated with their integration into the electric system.

In total, this report is the culmination of contributions from more than 110 individuals at more than 35 organizations (Appendix D lists the contributors to the study). Over the course of the project, an executive steering committee provided input from multiple perspectives to support study balance and objectivity. Technical reviewers from the renewable technology and electric sector industries, universities, public sector, non-profits, and other entities commented on a preliminary version of this report.

Most of the analysis informing the study, particularly the scenario assessment, was conducted in 2010. As a result, study assumptions concerning technology cost and performance and fossil energy prices were generally based on data available in late 2009 and early 2010. Where possible, more recent published work has been referenced; however, the implications of these publications may not have been fully reflected in the RE Futures study assumptions. For example, both the rapid development of domestic unconventional natural gas resources that has contributed to historically low natural gas prices, and the significant price declines for some renewable technologies (e.g., photovoltaics) since 2010, were not reflected in the study assumptions. Finally, the technology projections presented in RE Futures do not necessarily reflect the current DOE estimates.

RE Futures is documented in four volumes of a single report: Volume 1—describes the analysis approach and models, along with the key results and insights. Volume 2 describes the renewable generation and storage technologies included in the study; Volume 3 presents 2050 end-use demand and energy efficiency assumptions; and Volume 4 discusses some operational and institutional challenges of integrating high levels of renewable energy into the electric grid.

This Executive Summary, which is also included in Volume 1, highlights the analysis approach and key results from RE Futures. First, it summarizes the analysis approach, including scenario framework, renewable resources characterization, and modeling tools used to analyze the expansion of the U.S. electricity system and its operational characteristics. The key results from the analysis are then presented, including results associated with renewable technology deployment, grid operations, and economic, environmental and social implications. Finally, additional research opportunities are identified in the conclusions.

Analysis Approach

Scenario Framework

Given the inherent uncertainties involved with analyzing alternative long-term energy futures, and given the variety of pathways that might lead to higher levels of renewable electricity supply, multiple future scenarios were modeled and analyzed. The scenarios examined included the following considerations:

- **Energy Efficiency:** Most of the scenarios assumed adoption of energy efficiency (including electricity) measures in the residential, commercial, and industrial sectors that resulted in flat demand growth over the 40-year study period.[7]
- **Transportation:** Most of the scenarios assumed a shift of some transportation energy away from petroleum and toward electricity in the form of electric and plug-in hybrid electric vehicles, partially offsetting the electricity efficiency advances that were considered.[8]
- **Grid Flexibility:** Most scenarios assumed improvements in electric system operations to enhance flexibility in both electricity generation and end-use demand, helping to enable more efficient integration of variable-output renewable electricity generation.
- **Transmission:** Most scenarios expand the transmission infrastructure and access to existing transmission capacity to support renewable energy deployment. Distribution-level upgrades were not considered.
- **Siting and Permitting:** Most scenarios assumed project siting and permitting regimes that allow renewable electricity development and transmission expansion subject to standard land-use exclusions.

[7] The efficiency gains assumed are described in Volume 3. They do not represent an upper bound of energy efficiency, i.e., they were not as large as estimated by NAS/NAE (2010).

[8] The flat demand (low-demand) projection included this increase in demand from the transportation sector, whereas the business-as-usual demand (high-demand) projection did not. The contribution of biofuels to the transportation sector is not quantified in RE Futures.

In all the scenarios analyzed, only currently commercially available technologies (as of 2010) were considered, together with their incremental or evolutionary improvements despite the long-term (2050) timeframe, because the focus of this study was on grid integration and not on the potential advances of any individual technologies.[9] Technologies such as enhanced geothermal systems; ocean energy technologies (e.g., wave, tidal, current or ocean thermal); floating offshore wind technology; and others that are currently under development and pilot testing—and which show significant promise but are not yet generally commercially available—were not included.

More than two dozen scenarios were modeled and analyzed in this study as outlined in Figure ES-1 and detailed below. The number and diversity of scenarios allowed an assessment of multiple pathways that depended on highly uncertain future technological, institutional, and market choices. The framework included scenarios with specific renewable electricity generation levels to enable exploration of some of the technical issues associated with the operation of the U.S. electricity grid at these levels.[10] This scenario framework does not prescribe a set of policy recommendations for renewable electricity generation in the United States, nor does it present a vision of what the total mix of energy sources should look like in the future. Further, the framework does not intend to imply that one future is more likely than another.

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[9] RE Futures did not allow new nuclear plants, fossil technologies with CCS, as well as gasified coal without CCS (integrated gasification combined cycle) to be built in any of the scenarios presented in this report. Existing nuclear (and integrated gasification combined cycle) units, however, were included in the analysis, as were assumptions for the retirement of those units.

[10] The scenarios were not constructed to find the optimal GHG mitigation or clean energy pathway (e.g., to minimize carbons emissions or the cost of mitigating these emissions). In addition, because the scenarios included specific renewable generation levels, they were not designed to explore how renewable technologies might economically deploy under certain technology advancement projections without the generation constraints.

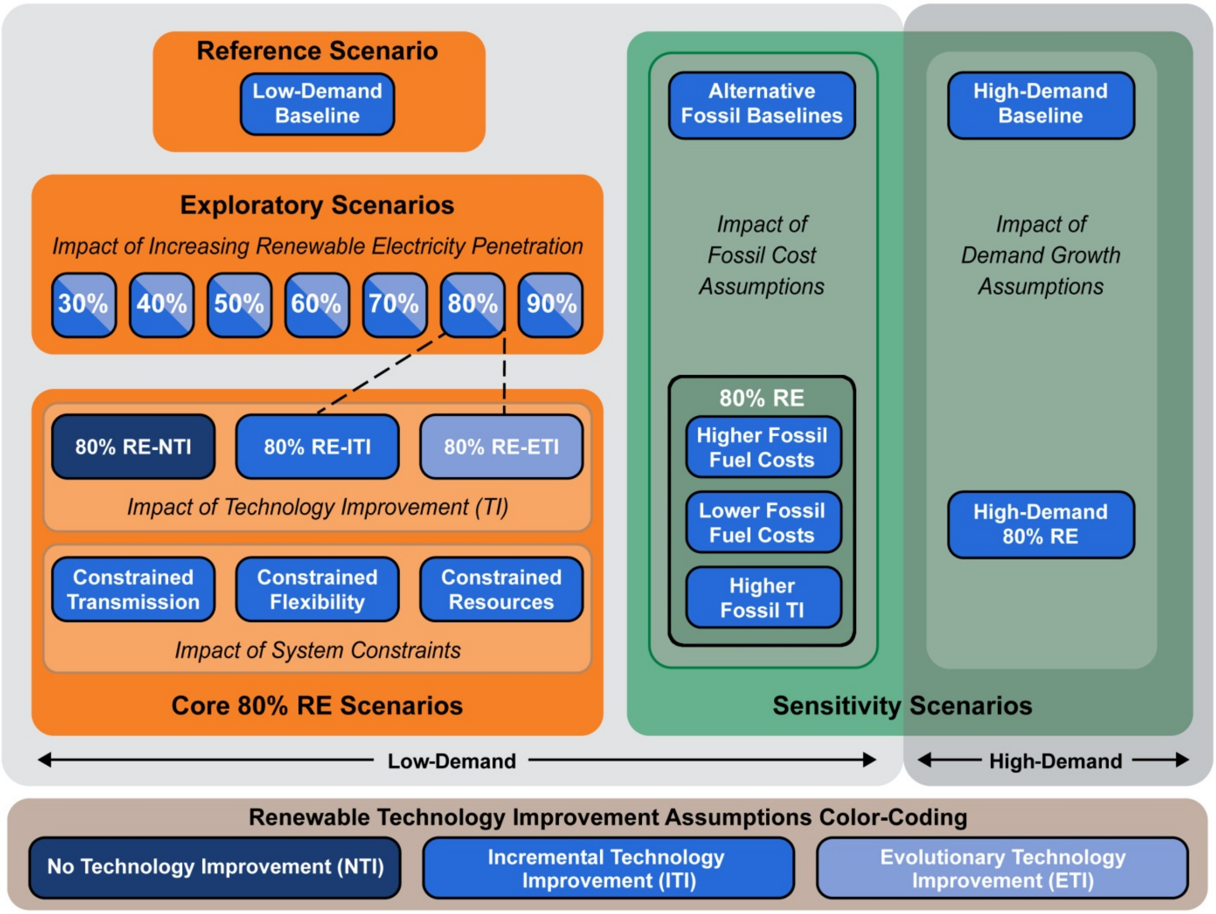

Figure ES-1. Modeling scenario framework for RE Futures

Dotted lines indicate that the 80% RE exploratory scenarios are the same as the 80% RE-ITI and 80% RE-ETI scenarios.

Low-Demand Baseline Scenario

A Low-Demand Baseline scenario was designed to reflect a largely conventional generation system as a point of comparison, or reference, for the high-penetration renewable electricity scenarios. The Low-Demand Baseline scenario assumes that a combination of emerging trends—including policies and legislation dealing with codes and standards, innovation in energy efficiency, and the green building and supply chain movements—drive the adoption of energy efficiency measures in the residential, commercial, and industrial sectors (see Volume 3 for details).[11] Substantial adoption of electric and plug-in hybrid electric vehicles was also assumed. In aggregate, these low-demand assumptions resulted in overall electricity consumption that exhibits little growth from 2010 to 2050. Existing state policies (e.g., renewable portfolio standards) and existing federal policies (e.g., investment tax credits, production tax credits, tax depreciation rules) were assumed to continue only as allowed under existing law, with no

[11] In addition to these trends, the primary historical drivers of electricity demand, population growth, and economic growth, were also considered in the construction of the scenario. While investment costs of these efficiency measures were not considered in the scenario development, findings from other studies generally indicate that such measures can be considered cost-effective or cost-competitive.

extensions. Expiration dates for existing federal policies vary, but generally are 2017 or earlier.[12] In combination with incremental technology improvements, these assumptions result in low levels of renewable electricity generation in the Low-Demand Baseline scenario.

Exploratory Scenarios

A series of "exploratory scenarios," in which the proportion of renewable electricity in 2050 increased in 10% increments from 30% to 90%, was evaluated. The primary purpose of these exploratory scenarios was to assess how increased levels of renewable electricity might impact the generation mix of renewable and non-renewable resources, the extent of transmission expansion in these cases, and the use of various forms of supply- and demand-side flexibility to enable a match between electricity supply and demand. These exploratory scenarios were evaluated under two distinct sets of renewable electricity technology advancement assumptions: Incremental Technology Improvement (ITI) and Evolutionary Technology Improvement (ETI).

Core 80% RE Scenarios

Further analysis was performed on six core 80% RE scenarios, each of which met the same 80%-by-2050 renewable electricity penetration level and each of which was designed to elucidate the possible implications of certain technological, institutional, and market drivers.[13] Three scenarios explored the impacts of future renewable energy technology advancements of currently commercial technologies and the resulting deployment of different combinations of renewable energy technologies[14]:

- The RE – No Technology Improvement (80% RE-NTI) scenario simply assumed that the performance of each renewable technology was maintained at 2010 levels for all years in the study period (2010–2050).
- The RE – Incremental Technology Improvement (80% RE-ITI) scenario reflected only partial achievement of the future technical advancements that may be possible (Black & Veatch 2012).
- The RE – Evolutionary Technology Improvement (80% RE-ETI) scenario reflected a more-complete achievement of possible future technical advancements (Volume 2). The RE-ETI scenario is not designed to be a lower bound and does not span the full range of possible futures; further technical advancements beyond the RE-ETI are possible.[15]

Three additional scenarios explored the impacts of different electricity system constraints based on assumptions that limited the building of new transmission, reduced system flexibility to

[12] Similarly, indirect incentives for conventional energy technologies—sometimes delivered through the tax code without sunset provisions —were assumed to be maintained as allowed under existing law. These same renewable and conventional technology policy assumptions were consistently applied to all the other scenarios as well.
[13] The specific assumptions used for these scenarios are discussed in Chapter 1.
[14] Although the methods used in RE Futures to project the future cost of each renewable electricity technology differ to some degree by technology, the resulting forecasts are largely based on anticipated scientific and engineering advancements rather than on learning-curve-based estimates that are endogenously driven by an assumed learning rate applied to cumulative production or installation. In reality, costs may decline in part due to traditional learning and in part due to other factors, such as research and development investment, economies of scale in manufacturing, component, or plant size, and reductions in material costs.
[15] Indeed, current DOE initiatives are focused on achieving substantially better cost and performance in many cases, with a target of achieving parity with conventional technologies.

manage the variability of wind and solar resources, and decreased renewable resource availability:

- The Constrained Transmission scenario evaluated how limits to building new transmission might impact the location and mix of renewable resources used to meet an 80%-by-2050 future.
- The Constrained Flexibility scenario sought to understand how institutional constraints to and concerns about managing the variability of wind and solar resources, in particular, might impact the resource mix of achieving an 80%-by-2050 future.
- The Constrained Resources scenario posited that environmental or other concerns may reduce the developable potential for many of the renewable technologies in question, and evaluated how such constraints could impact the resource mix of renewable energy supply.

High-Demand Scenarios

The scenarios described above—the Low-Demand Baseline scenario, the exploratory scenarios, and the six core 80% RE scenarios—were based on the low-demand assumptions, with overall electricity consumption that exhibits little growth from 2010 to 2050. To test the impacts of a higher-demand future, a scenario with the 80%-by-2050 renewable electricity generation but a *higher end-use electricity demand* was evaluated, with demand in 2050 30% higher than in the low-demand scenarios.[16] A corresponding reference scenario, the High-Demand Baseline scenario, with the same higher demand was also evaluated.[17]

Alternative Fossil Scenarios

Finally, given uncertainties in the *future cost of fossil energy sources*, the analysis included 80%-by-2050 RE scenarios in which: (1) the price of fossil energy (coal and natural gas) was both higher and lower than otherwise assumed in the other scenarios and (2) fossil energy technologies[18] experienced greater technology improvements over time than assumed in the other scenarios. Corresponding reference scenarios with these alternate fossil energy projections were also evaluated.

Renewable Resources Characterization

The United States has diverse and abundant renewable resources, including biomass, geothermal, hydropower, ocean, solar, and wind resources. Solar and wind are the most abundant of these resources. These renewable resources are geographically constrained but widespread—most are distributed across all or most of the contiguous states (Figure ES-2). Within these broad resource types, a variety of commercially available renewable electricity generation technologies have been deployed in the United States and other countries, including stand-alone biopower, co-fired

[16] The low-demand scenarios assume an annual growth rate of 0.17%; the high-demand scenarios assume an annual growth rate of 0.84%. Details on end-use energy demand assumptions are provided in Volume 3 of this report.
[17] For comparison, all high renewable electricity scenarios require a baseline or reference scenario that uses the same high-level assumptions regarding electricity demand.
[18] Consistent with the study's focus on commercially available renewable generation technologies, emerging fossil and nuclear technologies, such as carbon-capture and sequestration and modular nuclear plants, were not included.

biopower (in coal plants), hydrothermal geothermal, hydropower, distributed PV, utility-scale PV, CSP,[19] onshore wind, and fixed-bottom offshore wind.

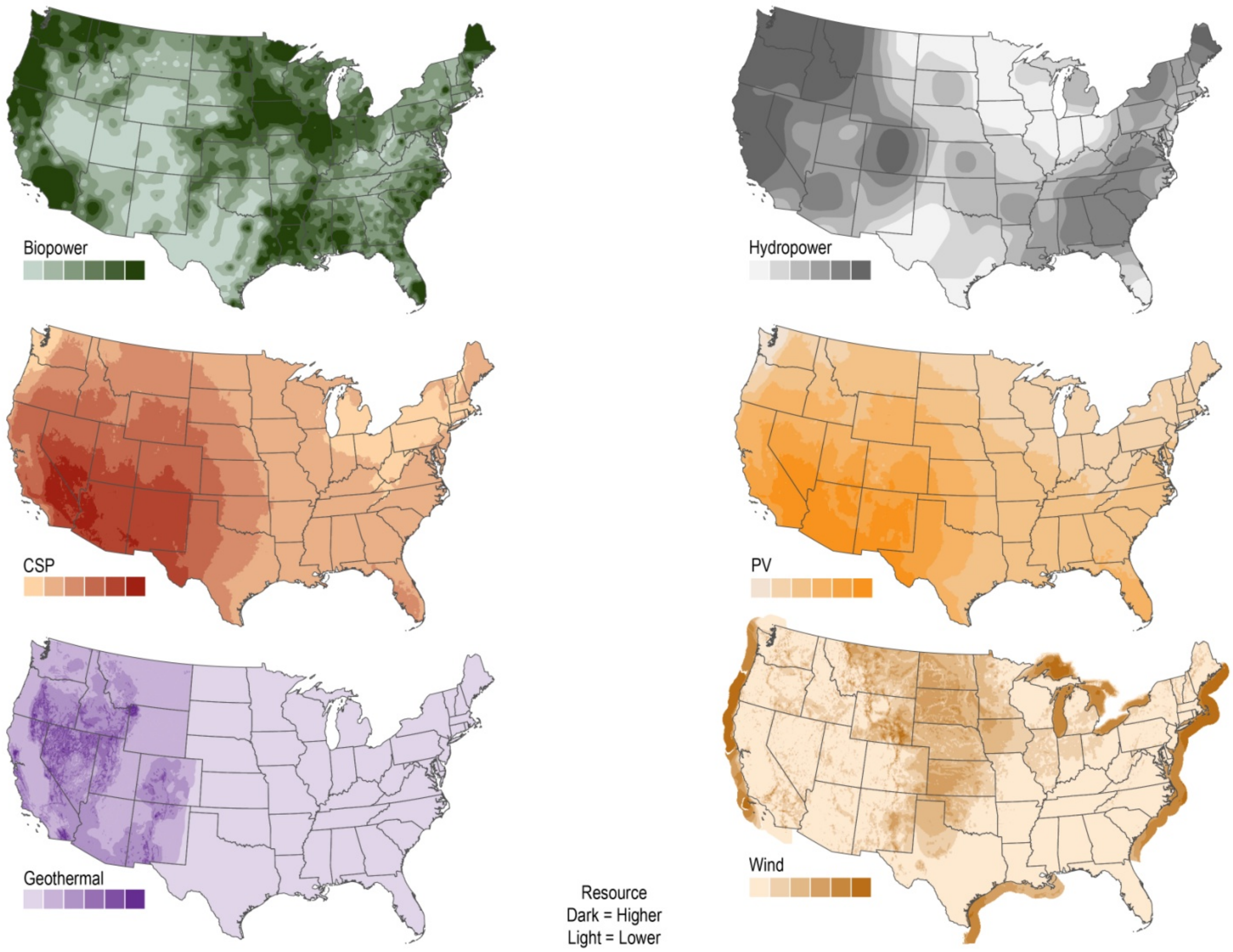

Figure ES-2. Geographic distribution of renewable resources in the contiguous United States

The United States has potential ocean energy and enhanced geothermal resources; however, these technologies were not modeled and therefore the resource potential is not included in this figure.

While only commercially available biomass, geothermal, hydropower, solar PV, CSP, and wind-powered systems were considered in the modeling analysis—only incremental and evolutionary advances in renewable technologies were assumed—the study describes a broad range of commercial and emerging renewable energy technologies in Volume 2, including the following[20]:

[19] In this report, CSP refers to concentrating solar thermal power. Concentrating photovoltaic technologies were not considered in the modeling analysis.
[20] The renewable resource characterizations described below and used in the models are based on historical climatic average resource patterns and have standard land area exclusions applied. After accounting for these standard exclusions, the aggregate renewable generation resource is many times greater than current electricity demand.

- **Biomass power** (Chapter 6, Volume 2) is generated by collecting and combusting plant matter and using the heat to drive a steam turbine. Biomass resources from agricultural and forest residues, although concentrated primarily in the Midwest and Southeast, are available throughout the United States. While biomass supply is currently limited, increased supply is possible in the future from increased production from energy crops and advanced harvesting technologies. DOE (2011) provides an estimate of 696–1,184 million annual dry tonnes of biomass inventory potential (of which 52%–61% represents dedicated biomass crops) in 2030.[21] The estimated biomass feedstocks correspond to roughly 100 GW of dedicated biopower capacity. Biopower can be generated from stand-alone plants, or biomass can be co-fired in traditional pulverized coal plants.
- **Geothermal power** (Chapter 7, Volume 2) is generated by water that is heated by hot underground rocks to drive a steam turbine. Geothermal resources are generally concentrated in the western United States, and they are relatively limited for hydrothermal technologies (36 GW of new technical resource potential), which rely on natural hot water or steam reservoirs with appropriate flow characteristics. Only commercially available hydrothermal technologies were included in the modeling analysis. Although not modeled, emerging technologies, including enhanced geothermal systems, engineered hydrothermal reservoirs, geopressured resources, low temperature resources, or co-production from oil and gas wells, could expand the geothermal resource potential in the United States by more than 500 GW.
- **Hydropower** (Chapter 8, Volume 2) is generated by using water—from a reservoir or run-of-river—to drive a hydropower turbine. Run-of-river technology could produce electricity without creating large inundated areas, and many existing dams could be equipped to generate electricity. The future technical potential of run-of-river hydropower from within the contiguous United States is estimated at 152–228 GW. Only new run-of-river hydropower capacity was considered in RE Futures modeling, and existing hydropower plants were assumed to continue operation. Other hydropower technologies, such as new generation at non-powered dams and constructed waterways, have the potential to contribute to future electricity supply, but they were not modeled in this study.
- **Ocean technologies** (Chapter 9, Volume 2) are not broadly commercially available at this time, and therefore were not modeled in this study, but both U.S. and international research and development programs are working to reduce the cost of the technologies. Ocean current resources are best on the U.S. Gulf and South Atlantic Coasts; wave energy resources are strongest on the West Coast. All resources are uncertain; preliminary estimates indicate that the U.S. wave energy technical potential is on the order of 2,500 TWh/yr. Other ocean technologies, including ocean thermal energy conversion technologies and tidal technologies, may also contribute to future electricity supply.

[21] To be conservative, for each modeled year, the analysis used feedstock estimates from Walsh et al. (2000) and Milbrandt et al. (2005), which are consistent with the low end of the DOE (2011) estimate for 2030, and did not assume any increase in resource over time; on the other hand, the analysis also did not include potential future growth in demand for biomass from the fuel sector. Maximum biopower capacity deployment was assumed to be roughly 100 GW in this study, with 27% from dedicated biomass crops.

- **Solar resources** (Chapter 10, Volume 2) are the most abundant renewable resources. They extend across the entire United States, with the highest quality resources concentrated in the Southwest. The technical potential of utility-scale PV and CSP technologies is estimated to be approximately 80,000 GW and 37,000 GW, respectively, in the United States. Distributed rooftop PV technologies are more limited, with approximately 700 GW available. PV technologies convert sunlight directly to electricity while CSP technologies collect high temperature heat to drive a steam turbine.
- **Wind resources** (Chapter 11, Volume 2) on land are abundant, extending throughout the United States, and offshore resources provide additional options for coastal and Great Lakes regions. Onshore and fixed-bottom offshore technologies are currently commercially available.[22] Floating platform offshore wind technologies that could access high-quality wind resources in deeper waters are less mature and were not considered in the modeling. Wind technical resource estimates exceed 10,000 GW in the contiguous United States.

Renewable resource supply varies by location and, in most cases, by the time of day and season. The electricity output characteristics of some renewable energy technologies also vary substantially, potentially introducing electric system operation challenges. A key performance characteristic of generators in general is their degree of dispatchability, specifically the ability of operators to control power plant output over a range of specified output generation levels. Conventional fossil plants are considered dispatchable, to varying degrees. Several renewable generator types, including biopower, geothermal, and hydropower plants with reservoir storage, are also considered dispatchable technologies in that system operators have some ability to specify generator output, if needed. Concentrating solar power with thermal storage can similarly be considered a dispatchable technology but is limited by the amount of storage. The output from run-of-river hydropower is generally constant over short time periods (minutes to hours) but varies over longer periods (days to seasons). Several emerging ocean technologies, such as ocean-current, may also provide fairly constant output and, in some cases, may be able to offer some level of dispatchability.

Wind and solar PV have little dispatchability—the output from these sources can be reduced, but not increased on demand. An additional challenge is the variability and uncertainty in the output profile of these resources, with wind and solar having limited predictability over various time scales. High levels of deployment of these generation types can therefore introduce new challenges to the task of ensuring reliable grid operation. However, it deserves note that the requirement for balanced supply and demand must be met on an *aggregate* basis—the variability and uncertainty of any individual plant or load entity does not ultimately define the integration challenge associated with high levels of variable renewable generation.

The analysis presented here focuses on electricity generation technology deployment, system operational challenges, and implications associated with specified levels of renewable generation, which represent the total annual renewable electricity generation from commercially available biomass, geothermal, hydropower, solar, and wind electricity generating technologies.

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[22] Although there are no offshore wind power plants operating in the United States, a number of projects have been proposed. In addition, offshore wind is widely deployed in Europe.

U.S. Electricity Grid Expansion and Operational Characterization

RE Futures employs two key models to characterize U.S. electricity grid operations with high levels of renewable generation. The NREL Regional Energy Deployment System (ReEDS) model explores the adequacy of the geographically diverse U.S. renewable resources to meet electricity demand over future decades. The ABB model, GridView, explores the hourly operation of the U.S. grid with high levels of variable PV and wind generation.[23] The linked-but-separate use of the two models, ReEDS and GridView, allows for a rich assessment of the technical, geographic, and operational aspects of renewable energy deployment.[24]

ReEDS is the analytical backbone of the study, providing estimates of the type and location of conventional and renewable resource development; the transmission infrastructure expansion requirements of those installations; and the composition and location of generation, storage, and demand-side technologies needed to maintain balance between supply and demand. ReEDS is unique among national, long-term capacity expansion models for its highly discretized regional structure and statistical treatment of the impact of variable wind and solar resources on capacity planning and dispatch. GridView was used to supplement the ReEDS analysis by modeling the hourly operation of the power system in 2050 for a subset of the high renewable scenarios. As one of the commercially available production cost models used by utilities, systems operators, and industry experts, GridView enables a more detailed exploration of the operational implications of a system with high levels of renewable electricity penetration through the use of an hourly time step, a more accurate representation of thermal generation ramp-rate limits, and a more realistic representation of transmission power flows compared with ReEDS.

These models were used to investigate a broad portfolio of supply- and demand-side options available to increase the flexibility of the electric system, including: having dispatchable renewable or conventional generators available to supply needed electricity when there is insufficient electricity generation from variable renewable plants; having the ability to provide reserves or change electricity demand through demand response (interruptible load) or transportation electric loads; deploying storage technologies for added system flexibility; and expanding the electric system transmission infrastructure to move more distant electricity supply to meet the load. Geospatial diversity was also taken into account, since it can assist in the integration of variable renewable generation because wind and solar plants that are located far apart generally have a combined output profile that is less variable than the individual plant profiles. Further, wind and solar resources may be uncorrelated or even anti-correlated depending on location; if so, combining their outputs would then further reduce aggregate variability.

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[23] The NREL Solar Deployment Systems (SolarDS) model was also used in RE Futures to represent rooftop PV deployment.

[24] In assessing high penetrations of variable renewable electricity, RE Futures addressed some aspects of electric system adequacy through statistical treatments of reserve requirements and hourly dispatch analysis; however, the analysis did not include a complete assessment of power system reliability (addressing such issues as stability, contingencies, and AC power flows). Similarly, RE Futures is not a fully detailed renewable energy integration study. Such studies typically seek to understand the impacts of variable and uncertain wind and solar generation on the operations of regional electric power systems and networks, relying on high time-resolution data and using methods that range from statistical analysis and production cost modeling to power flow simulations and steady state and transient grid analysis. RE Futures assessed electric system integration issues on a broader, national level, and the modeling tools used considered the variability and uncertainty of some renewable technologies, but not to the level of detail typical in integration studies.

Key Results

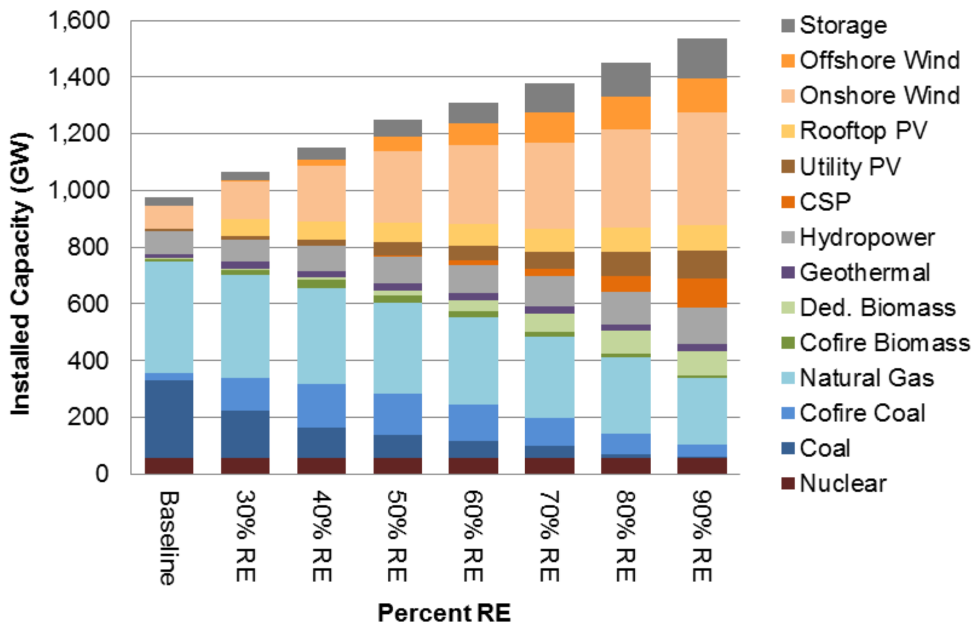
Deployment of Renewable Energy Technologies in High Renewable Electricity Futures

Renewable energy resources, accessed with commercially available renewable generation technologies, could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level. Figure ES-3 presents estimated 2050 capacity and generation, by technology, for the exploratory scenarios.[25] Generation from wind and PV technologies is variable, with lower capacity factors and relatively limited dispatchability. The growing deployment of this variable generation in these scenarios, increasing with renewable electricity penetration (from 20% in the baseline scenario to as high as 90% at the other end), drives the need for a growing amount of aggregate electric generation capacity in order to meet demand. Specifically, adequate capacity from dispatchable resources is required to ensure delivery of necessary generation year-round.

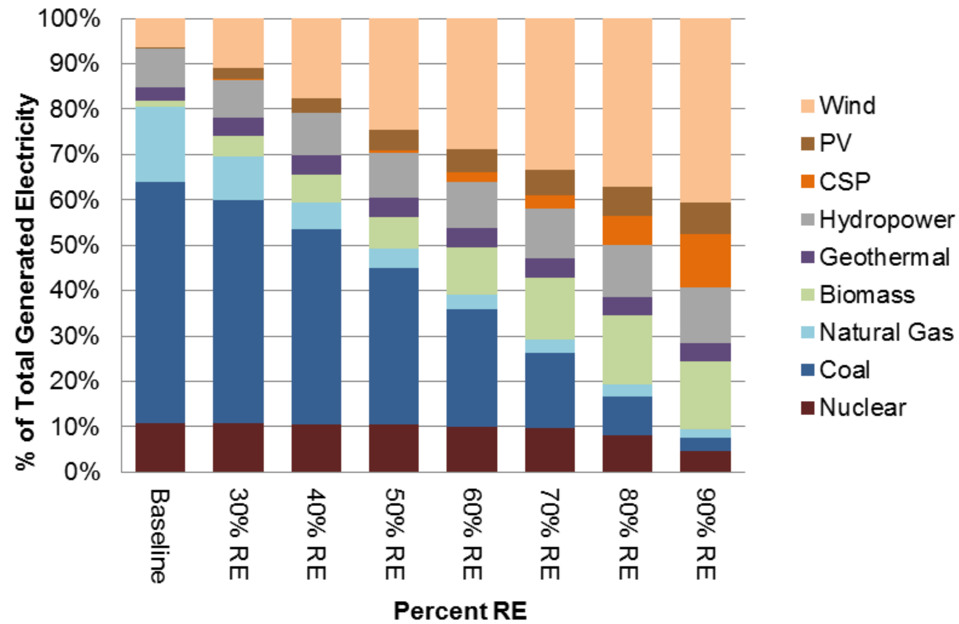
Commercially available renewable technologies were deployed in the modeling to varying degrees in the exploratory scenarios, in part to exploit geographic and temporal diversity in achieving high renewable electricity penetration levels. Onshore wind was found to contribute most significantly in these exploratory scenarios, with offshore wind becoming an increasingly important player as higher renewable electricity levels were achieved. Among the solar technologies, PV (utility-scale and rooftop, combined) was generally found to play a more-sizable role than CSP under the relatively lower renewable penetration scenarios. Electricity supply from CSP was projected to grow more rapidly under the higher renewable penetration scenarios, in part because CSP with thermal storage provides added dispatchability. Both dedicated and co-fired biomass were also found to contribute significantly to the renewable energy mix, with a shift from co-firing to dedicated biomass plants as renewable electricity penetration levels increased. Geothermal and hydropower were found to contribute proportionately less than the other renewable energy sources, especially under the highest renewable electricity scenarios considered, due to assumed resource and cost constraints.[26] However, even for this limited set of geothermal and hydropower resources, capacity expansion was substantial relative to recent trends, and much of the estimated available resource potential was accessed. Enhanced geothermal systems, ocean energy, and floating platform offshore wind energy were not considered, but these technologies may offer large resource potential, additional diversity, and regional advantages if technological advancements enable commercialization.

[25] Deployment results shown in Figure ES-3 used the renewable electricity incremental technology improvement (RE-ITI) assumptions. Results for the RE-ETI scenarios are included in Chapter 2.

[26] The assumptions used in the analysis were particularly constraining on geothermal technologies, for which advanced technologies, such as enhanced geothermal systems that can tap large quantities of energy inside the earth, were not considered in the grid modeling. The modeling analysis focused on currently commercial technologies only.



(a) Capacity mix in 2050 for the exploratory scenarios



(b) Generation mix in 2050 for the exploratory scenarios

Figure ES-3. Installed capacity and generation in 2050 as renewable electricity levels increase (low-demand, RE-ITI technology improvement)

All regions of the United States could contribute substantial renewable electricity supply in 2050, consistent with their local renewable resource base. Figure ES-4 presents the modeled location of renewable electricity generation and capacity by 2050 for one 80%-by-2050 RE scenario (80% RE-ITI). It also compares total regional electricity generated in 2050 to regional electricity demand (based on low-demand assumptions). In the scenario shown, wind energy supply was significant in most regions but was most prominent in the Great Plains, Great Lakes, Central, Northeast, and Mid Atlantic regions (with a large fraction of wind generation coming from offshore resources in the Northeast and Mid Atlantic regions). Solar energy was found to deploy most substantially in the Southwest (dominated by CSP), followed by California and Texas (CSP and PV), and then by the Florida and the Southeast regions (dominated by PV). Biomass supply was most significant in the Great Plains, Great Lakes, Central, and Southeast regions. Hydropower supply was most significant in the Northwest, but hydropower was also a sizable contributor in California, the Northeast, and the Southeast. Geothermal was found to deploy primarily in California and the Southwest.

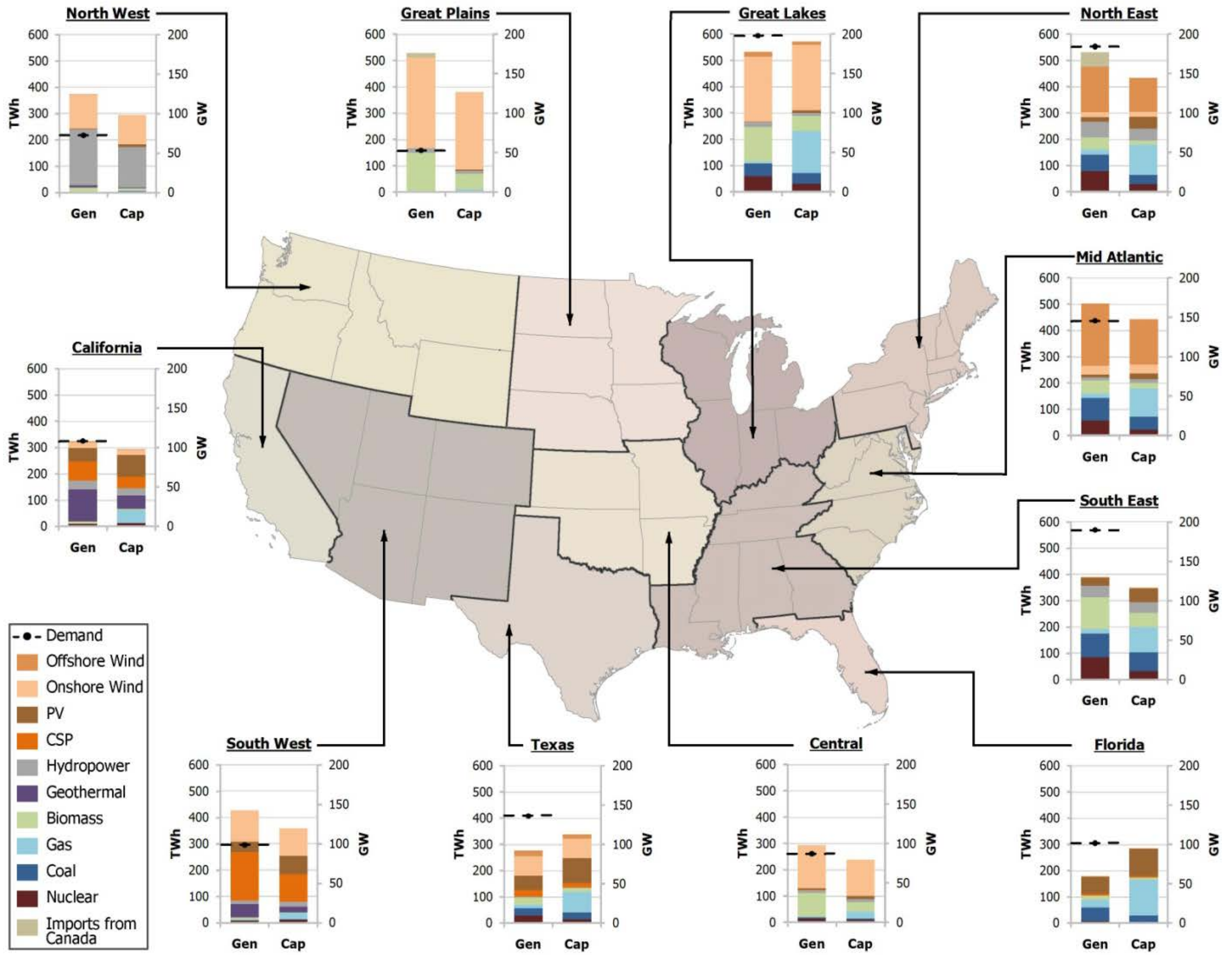


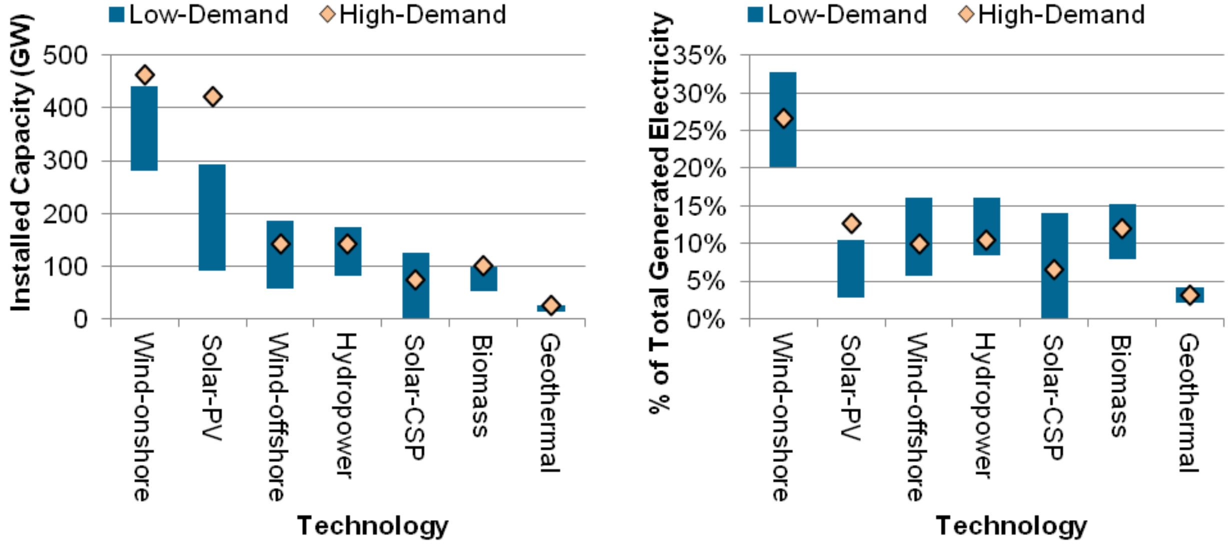
Figure ES-4. Renewable generation and capacity in 2050 by region under 80% RE-ITI scenario (low-demand, RE-ITI technology improvement)

Multiple technology pathways exist to achieve a high renewable electricity future. Assumed constraints, which limit power transmission infrastructure, grid flexibility, or the use of particular types of resources can be compensated for through the use of other resources, technologies, and approaches. The renewable energy resource base of the United States is both abundant and diverse. As a result, a central finding of the analysis is that there are many possible ways to achieve high renewable penetration levels.

For example, the technology improvement scenarios included in the six core 80% RE scenarios (Impact of Technology Improvement scenarios) showed that technologies that are currently at earlier stages of commercialization (e.g., solar) could achieve greater deployment if significant technology improvements were realized in the future. In contrast, if these improvements were not realized, currently more commercially mature technologies (e.g., onshore wind) could deploy to a greater extent. Also, a set of scenarios included in the core 80% RE scenarios explored the impacts of limits on building new transmission, constraints on the flexibility of the electric system to manage the variability of wind and solar resources, and constraints on the developable potential for many renewable technologies (Impact of System Constraints scenarios). The mix of renewable resources deployed and the deployment of flexible supply- and demand-side technologies were significantly impacted in these scenarios. In particular, when new transmission builds were constrained, greater deployment was observed for resources located closer to load centers, including PV, offshore wind, and biomass. A future where the flexibility of the electric system was limited resulted in a shift of renewable electricity supply away from variable wind and PV technologies and toward more dispatchable options, particularly CSP with thermal storage, and to storage technologies. When the assumed availability of renewable energy supply was reduced—due to siting or permitting challenges, for example—the contributions from the most resource-constrained technologies (biopower, geothermal, and hydropower) declined, while more abundant wind and solar resources were used to a greater degree. Figure ES-5 shows the range in 2050 capacity and generation by technology among the six low-demand 80%-by-2050 RE scenarios examined. Although the type and quantity of renewable technologies deployed in these scenarios varied significantly, estimated direct electric sector aggregate cost was relatively insensitive to most of these variations.[27]

Finally, the analysis found that the renewable resource base in the United States was sufficient to support 80% renewable electricity generation by 2050 in a higher demand growth scenario. Figure ES-5 also shows 2050 deployment results for the High-Demand 80%-by-2050 RE scenario, which features a much greater amount of solar capacity compared with the low-demand scenarios.

[27] See individual technology chapters in Volume 2 for a discussion of the specific scenarios that lead to high and low estimates for each technology individually; Volume 1 provides more discussion of the operational and cost implications these scenarios.



(a) 2050 installed capacity by technology

(b) 2050 contribution to total generated electricity

Figure ES-5. Range of 2050 installed capacity and annual generated electricity by technology for the low-demand core 80% RE scenarios and the High-Demand 80% RE scenario

Annual renewable capacity additions that enable high renewable electricity are consistent with current global production capacities but are significantly higher than recent U.S. annual capacity additions for the technologies considered. No insurmountable long-term constraints to renewable electricity technology manufacturing capacity, materials supply, or labor availability were identified. The analysis showed that achieving high renewable electricity futures would require a sustained increase in renewable capacity additions. In the core 80% RE scenarios, average annual renewable capacity additions of 19–22 GW/yr from 2011–2020 were estimated, increasing to a maximum rate of 32–46 GW/yr from 2041–2050. Given recent historical experience with U.S. renewable electricity capacity additions (11 GW in 2009 and 7 GW in 2010),[28] achieving these rates of deployment may pose challenges as production ramps up, including those related to materials availability, equipment manufacturing capacity, labor needs, and project development and siting processes. However, no insurmountable long-term technical constraints to renewable technology manufacturing capacity, materials supply, or labor availability were identified; better informed siting practices and regulations can mitigate potential constraints related to project development and siting processes (see Chapter 3 and Volume 2).

Growth in renewable capacity additions in the United States and globally over the last decade has been considerable, and it demonstrates the ability to scale manufacturing and deployment at a rapid pace. The wind power additions required in the scenarios, for example, were substantial,

[28] The challenges associated with the rates of deployment presented here depend on technology. For example, renewable installations in the United States in recent years were dominated by new wind technologies; therefore, achieving the deployment rates envisioned in the scenarios for wind energy would likely be less challenging from an industry growth perspective compared with other technologies.

but historical growth in manufacturing and installation suggests that manufacturing need not be a major constraint to the continued growth that would be necessary to meet an 80%-by-2050 generation level. The biopower and geothermal additions resulting from the scenario modeling, although greater than recent historical trends, are similarly unlikely to place undue strain on supply chains. The estimated rate of PV deployment is particularly high, but PV manufacturing and deployment are highly scalable, and worldwide PV production capacity has been growing rapidly and is already comparable to the deployment rates projected in high renewable scenarios presented here for the United States. Moreover, many of the renewable technologies are based on common materials that are not supply-constrained. Even for PV, which does use some materials that may be supply-constrained, worldwide production capacity is already sizable and that capacity continues to expand rapidly. In addition, alternate approaches exist to reduce dependence on supply-constrained materials if necessary. While a comprehensive analysis of industry scale-up, including labor demands and access to critical materials, is beyond the study scope, the initial analysis did not identify any insurmountable technical challenges associated with industry scale-up at the technology deployment levels considered.

Grid Operability and Hourly Resource Adequacy in High Renewable Electricity Futures

Electricity supply and demand can be balanced in every hour of the year in each region with nearly 80% of electricity from renewable resources, including nearly 50% from variable renewable generation, according to simulations of 2050 power system operations.[29] Although a full reliability assessment is beyond the scope of this analysis, hourly production simulation did consider unit commitment with imperfect forecasts, DC optimal power flow, and thermal generator flexibility limits (e.g., ramp rates and minimum generation levels). Figure ES-6 shows nationwide dispatch by generator type during the annual peak coincident load (Figure ES-6[a]) and during the lowest coincident load of the year (Figure ES-6[b]) in 2050 for a high renewable electricity scenario. The operational simulations did not project any hours of unserved load during the peak load hour, lowest coincident load hour, or any other hour of the year.[30]

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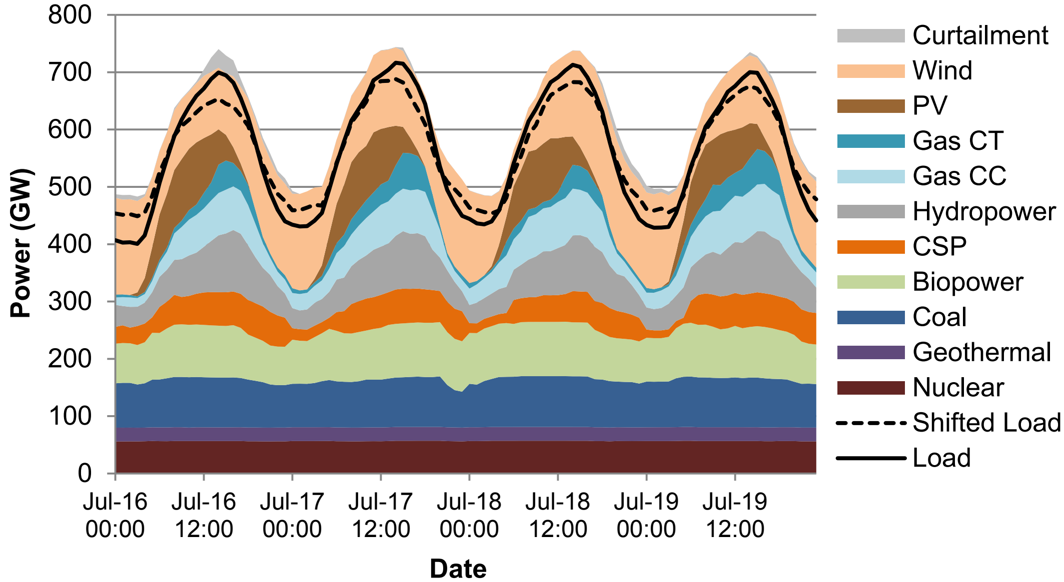
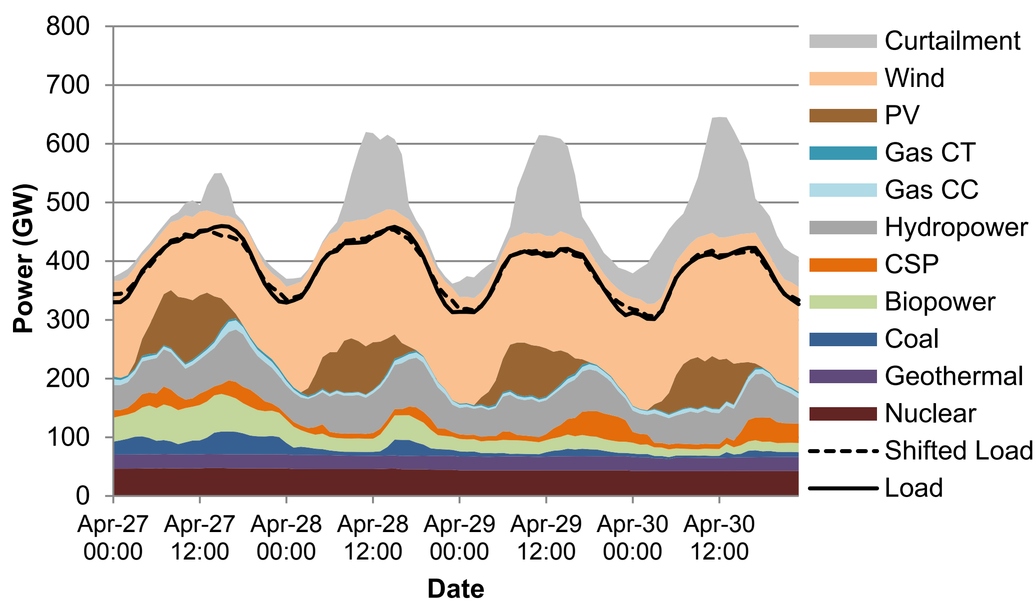
[29] Although the capacity expansion modeling (ReEDS) planned for renewable resources to contribute 80% of annual generation in 2050, the hourly operational model (GridView) simulated roughly 75%, in part due to a lack of a renewable generation requirement. GridView model dispatch decisions were based on the variable cost of generation and did not consider the renewable or non-renewable nature of the generation source.

[30] The electric system is a complex system of systems that operates on many time scales ranging from milliseconds to years; ultimately, analyses must be conducted to address all of the potential operating aspects of future electricity generation systems as they evolve. Electric system operations are described in detail in Volume 4.



(a) Summer peak load in 2050



(b) Lowest coincident load in 2050

Figure ES-6. Hourly dispatch stacks for the 80% RE-ITI scenario[a]

[a] The solid black line representing “load” includes charging of electric vehicles. The broken line representing “shifted load” represents “load” minus storage. The Gas CT category includes a small number of oil-fired units. The unit types are ordered (subjectively) from least variable or flexible (at the bottom) to most variable (at the top).

Additional challenges to power system planning and operation would arise in a high renewable electricity future, including management of low-demand periods and curtailment of excess electricity generation. The hourly analysis also found that, in contrast to today's fossil-fuel-dominated electricity system for which the time of peak load (e.g., summer afternoons) is of most concern, operational challenges for high renewable generation scenarios were most acute during low-demand periods (e.g., spring evenings) when the abundance of renewable supply relative to demand would force thermal generators to cycle or ramp down to their minimum generation levels.[31] During low-demand periods in today's system and in the baseline scenario, most of the peaking needs are met with hydropower and combined cycle units; combustion turbines are needed but to a much lesser extent than in the summer. Although the load characteristics in 2050 are similar in the baseline scenario and the high renewable scenarios, during low-demand periods in the latter (e.g., Figure ES-6[b]), there was enough aggregate renewable electricity to fully serve load, causing the net load (load minus variable wind and PV generation) to be much more variable compared to the rest of the year. This increased variability in net load creates challenges associated with greater power plant cycling and ramping.

A primary challenge of variable renewable energy integration at higher levels of penetration is the need at times to curtail excess electricity, particularly during periods with low electricity demands.[32] The hourly dispatch analysis estimated that overall in 2050, 8%–10% of wind, solar, and hydropower generation would need to be curtailed under an 80%-by-2050 RE scenario. Curtailments reduce capacity factors and introduce uncertainty in electricity sales, thereby negatively impacting plant economics. A variety of technical and institutional approaches could be applied to reduce these levels of curtailment. First, additional transmission capacity in congested corridors would help alleviate congestion and reduce curtailment. Second, increasing the size of reserve-sharing groups could help reduce the number of inflexible generators online to provide spinning reserves; curtailment of renewable generation could be reduced if fewer plants operate at minimum levels. Third, the flexibility of the thermal fleet could be improved, or market structures could be implemented to encourage the operation of more flexible generators. Fourth, additional energy storage and controllable loads could be used to improve system flexibility. Finally, new or existing industries could take advantage of the low-cost electricity available during seasons or times when curtailment would have occurred, and the resulting increased demand could then consume electricity that otherwise would have been curtailed.

Electric sector modeling shows that a more flexible system is needed to accommodate increasing levels of renewable generation. System flexibility can be increased using a broad portfolio of supply- and demand-side options and will likely require technology advances, new operating procedures, evolved business models, and new market rules. As renewable electricity generation increased from 20% in the baseline scenario to 90% in the exploratory scenarios, the annual contribution from *variable* generation (wind and solar PV) grew from 7% to 48% in 2050. At

[31] Peak load still requires management and will be challenging for the same reasons it is today, but in addition, management of low-demand periods and curtailment will be required with high variable renewable electricity.

[32] This situation parallels the use of combustion turbines in conventional systems, which are typically used just a few hundred hours per year to meet summer peak loads and are largely idle much of the rest of the year. As such, both the conventional and the high renewable electricity systems operate with excess capacity most of the time. While the high renewable system generates power with the excess capacity as long as resources are available, the conventional system simply leaves the excess capacity idle.

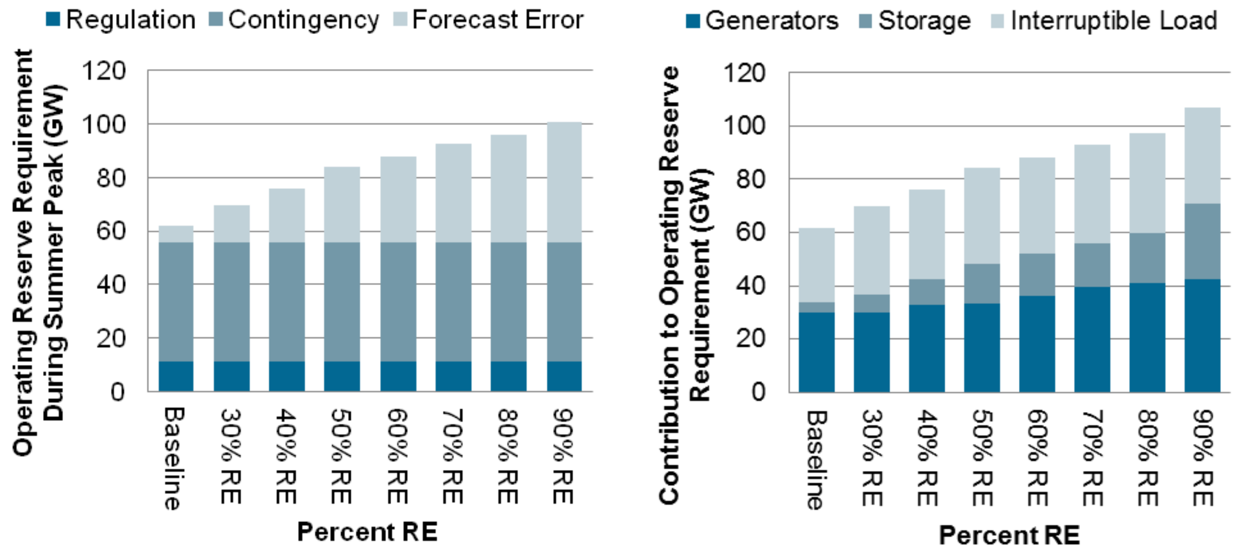
this high level of variable generation, ensuring a real-time balance between electricity supply and demand is more challenging The variability and uncertainty associated with these high levels of wind and PV penetration were found to be manageable through the application of adequate flexible generation capacity, the use of grid storage and demand-side technologies, the expansion of transmission infrastructure, and greater conventional plant dispatch flexibility, including significant daily ramping of fossil generators. (Dispatchable renewable technologies, like conventional technologies, do not impose significant additional challenges to system operability, and they are also used to help manage wind and solar PV integration.)

The RE Futures analysis considers reserves necessary for reliable electric system operations, spanning a wide range of timescales (from long-term planning reserves to short-term operating reserves). The same capacity reserve margin requirements were satisfied across all scenarios despite the relatively low capacity values of variable resources and their increasing deployment as renewable penetration increased. Partly to satisfy planning reserve requirements, greater aggregate capacity was needed in high penetration renewable scenarios (see Figure ES-3).

Additional operating reserves were also found to be required in high variable renewable generation systems and were accommodated through the availability of conventional power plants, storage technologies, and demand-side practices. The analysis included multiple components of operating reserves, namely contingency reserves, frequency regulation reserves, and reserves associated with imperfect forecasts of wind and PV generation. Figure ES-7 shows how operating reserve requirements increased as renewable deployment increased and the different options used to meet these requirements in the exploratory scenarios.[33] Although operating reserve *requirements* increase with wind and PV deployment (due to greater forecast errors), because the dispatch of existing conventional power plants declines to accommodate additional wind and PV generation, these existing conventional units were found to be more available to satisfy the necessary operating reserve requirements. In other words, a high renewable electricity future would reduce the energy-providing role of the conventional fleet and increase its reserve-providing role.

The analysis found use of storage to be an attractive option to increase electric system flexibility due to the ability of storage to shift load to better correlate with output from variable generators, reduce curtailments by storing excess generation in times of low demand, and provide firm capacity for a variety of reserve services. In the core 80% RE scenarios, for example, storage deployment was found to increase from approximately 20 GW in 2010 to 100–152 GW in 2050. Demand-side options were also found to play a significant role in meeting the integration challenges of a high renewable electricity future. For example, in the core 80% RE scenarios, 28–48 GW of demand-side interruptible load were deployed in 2050, compared with just 15.6 GW deployed in 2009.

[33] In Figure ES-7, the total contribution to operating reserves exceeds the requirement due to the fact that only one time (summer peak) is shown, while certain reserve-types (e.g., interruptible load) are annual in nature and deployed to serve other times not shown.



(a) 2050 operating reserve requirement during the summer peak by reserve type

(b) 2050 contributions toward total operating reserve requirement by technology type

Figure ES-7. Operating reserve requirements as renewable electricity levels increase

The RE Futures analysis suggests that variable generation levels of up to nearly 50% of annual electricity can be accommodated when a broad portfolio of supply- and demand-side flexibility resources is available at a level substantially higher than in today's electricity system. A broad portfolio of flexible supply- and demand-side resources and options were made available in the scenario modeling, and were relied upon particularly in the high renewable generation scenarios, including:

- Maintaining sufficient capacity on the system for planning reserves
- Relying on demand-side interruptible load, conventional generators (particularly natural gas generators), and storage to manage increased operating reserve requirements
- Mitigating curtailment with storage and controlled charging of electric vehicles
- Operating the system with greater conventional power plant ramping
- Relying on the dispatchability of certain renewable technologies (e.g., biopower, geothermal, CSP with storage and hydropower)
- Leveraging the geospatial diversity of the variable resources to smooth output ramping
- Transmitting greater amounts of power over longer distances to smooth electricity demand profiles and meet load with remote generation

Achieving the system flexibility required to integrate high levels of renewable generation will require some combination of technology advances, new operating procedures, evolved business models, and new market rules. Although the analysis does not examine how these mechanisms could be implemented, it does describe the power system flexibility characteristics needed for the integration of high levels of renewable generation.

Transmission Expansion in High Renewable Electricity Futures

As renewable electricity generation increases, additional transmission infrastructure is required to deliver generation from cost-effective remote renewable resources to load centers, enable reserve sharing over greater distances, and smooth output profiles of variable resources by enabling greater geospatial diversity. Many of the system flexibility resources and options described above can benefit from transmission infrastructure enhancements to enable the transfer of power and sharing of reserves over large areas to accommodate the variability of wind and solar electricity generation in combination with variability in electricity demand. With high penetrations of variable generation, net load (load minus variable generation) in a specific region can show dramatic ramps. Transmission between regions helps reduce ramps in net load because it allows system operators to access a larger pool and more diverse mix of variable generation, with some smoothing of output profiles and demand profiles over larger geographic areas. Figure ES-8 shows projected new transmission capacity deployed over the 40-year study period for the exploratory scenarios. Demands for new transmission capacity are much greater in the higher renewable generation scenarios than in lower renewable generation scenarios, outstripping the effects of the low-demand assumption, reductions in transmission use by conventional fossil generation (freeing up the lines for renewable generation), and deployment of renewable resources that are proximate to load centers (e.g., PV and offshore wind).[34] The increase in transmission needs as renewable electricity supply grows, for all 80%-by-2050 renewable electricity scenarios, result in an average annual projected transmission and interconnection investment that is within the recent historical range for total investor-owned utility transmission expenditures in the United States (i.e., $2 billion/yr to $9 billion/yr from 1995 through 2008) (Pfeifenberger et al. 2009).

[34] The analysis assumed that the existing transmission infrastructure is operational throughout the study period and did not consider maintenance needs for the existing transmission lines or other infrastructure. In addition, the analysis did not consider distribution-level maintenance or upgrades.

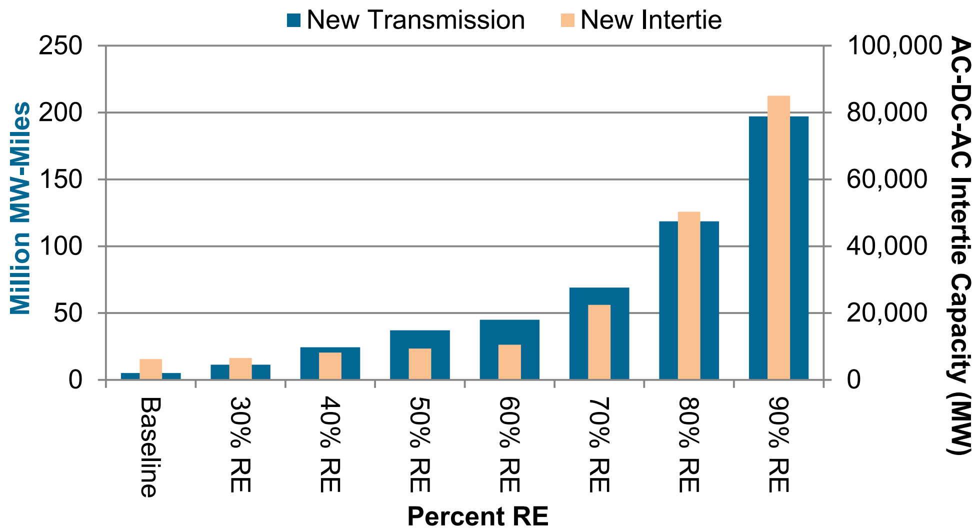


Figure ES-8. New transmission capacity requirements in the baseline and exploratory scenarios

Existing total transmission capacity in the contiguous United States is estimated at 150–200 million MW-miles[35]

New transmission in the high renewable electricity scenarios was found to be concentrated in the middle and southwestern regions of the United States, mainly to access the high-quality wind and solar resources in those regions and to deliver generation from those resources to load centers. For example, Figure ES-9 presents a conceptual map of new transmission infrastructure needed in an 80%-by-2050 scenario. As shown in Figure ES-9 and quantified in Figure ES-8, the current isolation of the three asynchronous interconnections—Western Electricity Coordinating Council (WECC), Electric Reliability Council of Texas (ERCOT), and Eastern Interconnection—was greatly reduced in many of the high renewable electricity scenarios through the expansion of AC-DC-AC interties. This expansion enabled the East to have greater access to the high-quality renewable resources located in the western United States, although the hourly simulations and DC transmission power flow analysis suggests that these east-west transmission linkages were used bi-directionally to manage temporal variations in electricity supply and demand. Expanding interties between the three asynchronous interconnections was found to be desirable in many of the high renewable scenarios; however, results from the Constrained Transmission scenario showed that an 80%-by-2050 RE scenario was achievable even when such expansion was not allowed.

Significant institutional obstacles, including constraints in siting new transmission lines, cost allocation concerns with transmission projects, and coordination between multiple governing entities, currently inhibit transmission expansion. The mechanisms to overcome these obstacles were not explored in the study, but the analysis demonstrates that additional long-distance transmission capacity can be an important characteristic of high renewable electricity futures.

[35] The ReEDS model assumed 150 million MW-miles of existing inter-BA transmission capacity; the 200 million MW-mile estimate is from Homeland Security Infrastructure Database (2008) and other sources.

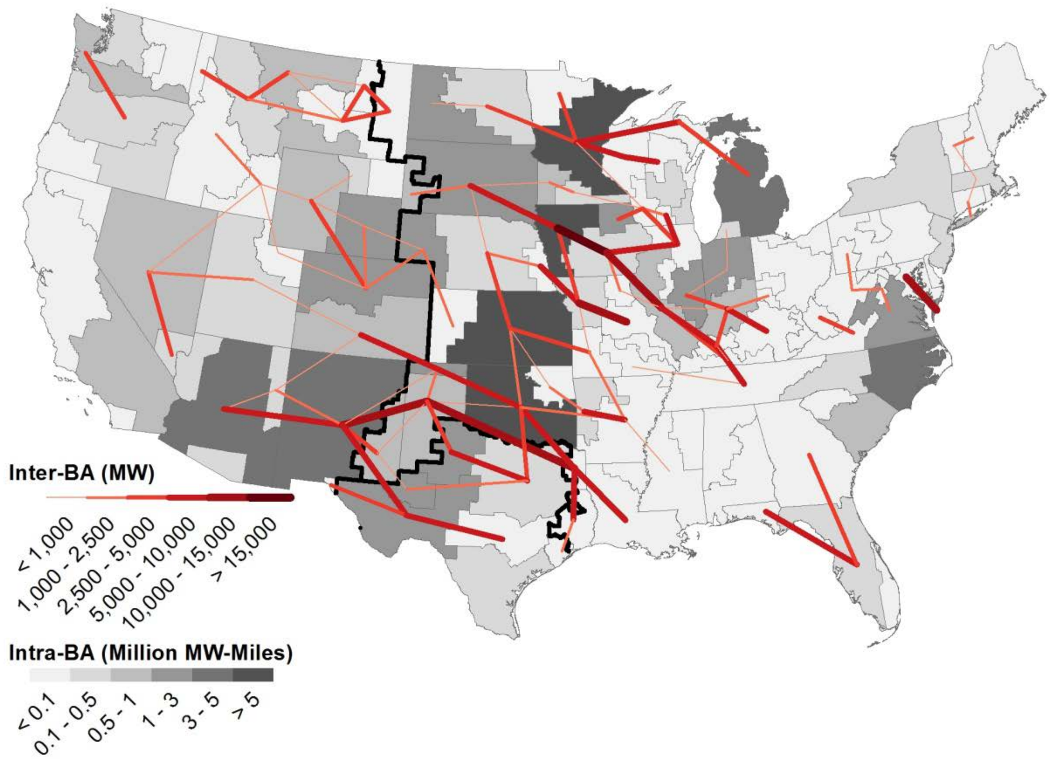


Figure ES-9. New transmission capacity additions and conceptual location in the 80% RE-ITI scenario

Cost and Environmental Implications of High Renewable Electricity Futures

High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use. Direct environmental and social implications are associated with the high renewable futures examined, including reduced electric sector air emissions and water use resulting from reduced fossil energy consumption, and increased land use competition and associated issues. At 80% renewable electricity in 2050, annual generation from both coal-fired and natural gas-fired sources was reduced by about 80%, resulting in reductions in annual greenhouse gas emissions of about 80% (on a direct combustion basis and on a full life cycle basis) and in annual power sector water use of roughly 50%. At 80% renewable electricity, gross land-use impacts associated with renewable generation facilities, storage facilities, and transmission expansion totaled less than 3% of the land area of the contiguous United States.[36]

The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Improvement in the cost and performance of renewable technologies is the most impactful lever for reducing this incremental cost. The retail electricity price implications estimated for the 80%-by-2050 RE scenarios are comparable to those seen in other studies with similarly transformative electricity futures, as shown on Figure ES-10. Low carbon and clean energy scenarios, evaluated by the U.S. Energy

[36] Net land-use impacts, considering the implications of reduced conventional generation, and land-use impacts based on disrupted lands, are both expected to be smaller. As an example of the latter case, disrupted land would generally be less than 5% of gross land area for wind generation facilities.

Information Administration (EIA) and the U.S. Environmental Protection Agency (EPA), with avoided carbon emissions trajectories similar to the core 80% RE scenarios showed increases in average retail electricity prices (relative to their own reference scenarios) in 2030 of $9–$26/MWh, rising to $41–$53/MWh by 2050. These studies generally considered a portfolio of clean generation technology options, including renewable, nuclear, and low emissions fossil. The estimated incremental price impacts of the core 80% RE scenarios are comparable to these estimates.

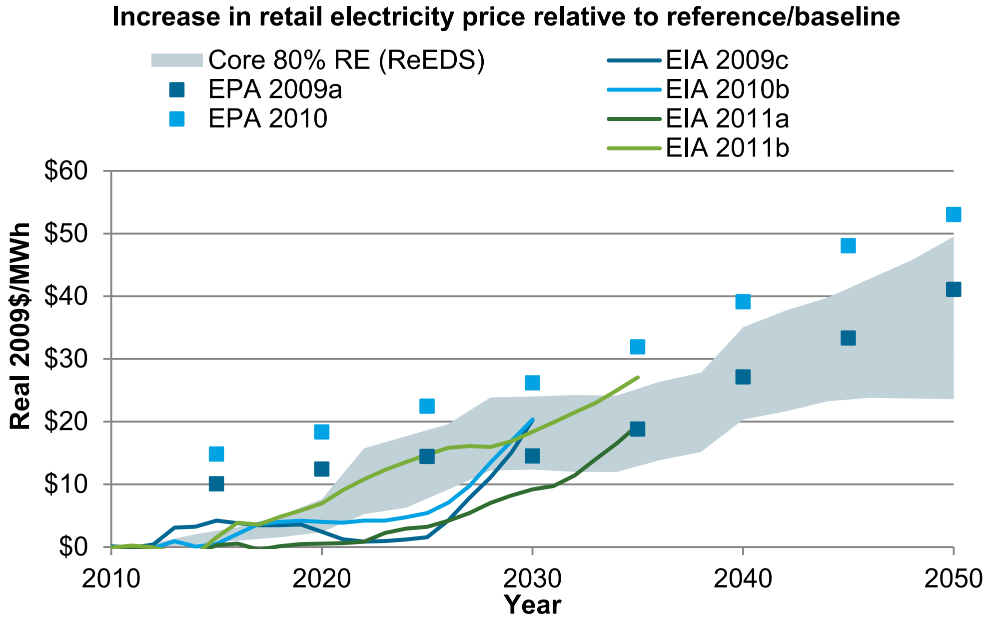


Figure ES-10. Average increase in retail electricity rates relative to study-specific reference/baseline scenarios

EIA 2011a and 2011b document analysis of clean energy scenarios. EIA 2009, EPA 2009, EIA 2010, and EPA 2010 report on analysis of several low carbon emissions scenarios.

As with these other clean generation scenarios that would represent a nearly wholesale transformation of the U.S. electricity system, the high renewable generation scenarios examined show a direct incremental cost relative to the continued evolution of today's conventional generation-dominated system. Higher electricity prices associated with the high renewable scenarios are driven by replacement of existing generation plants with new generators (mostly renewable); additional balancing requirements reflected in expenditures for combustion turbines, storage, and transmission; and the assumed higher relative capital cost of renewable generation, compared to conventional technologies, assumed in the analysis. The increased capital investments associated with these drivers, compared to the baseline scenario, were not fully offset by cost savings associated with lower fossil energy consumption. The incremental cost does not include investments in energy efficiency implied by low electricity demand assumptions, or the savings in avoided generation resulting from these investments. Further, the incremental cost estimate does not consider indirect societal costs associated with the scenarios (e.g., associated with the greenhouse gas emissions described above), or economy-wide impacts.

Advancements in renewable technologies, reflected by technology cost and performance improvement assumptions, had the greatest impact on the incremental cost of the high renewable generation scenarios. For example, the low end of the range of incremental electricity price shown in Figure ES-10 reflects the scenario with the highest assumed renewable technology improvement (RE-ETI), while the high end reflects the lowest technology improvement scenario (RE-NTI).[37] Assumed system constraints had more modest impact on direct incremental costs; scenarios reflecting constraints to transmission expansion, renewable resources, and grid flexibility all had similar costs, which fell well within the bounds identified in Figure ES-10. Finally, incremental costs were largely insensitive to differences in projections for fossil fuel prices and fossil technology improvements.

The lower renewable generation levels examined in the exploratory scenarios showed lower incremental 2050 retail electricity prices. For example, the 30% RE scenario under highest technology improvement assumptions (RE-ETI) showed no price increase in 2050 relative to the baseline scenario (which used RE-ITI assumptions). This result suggests that significant expansion of renewable generation beyond the 2010 level (10% of total generation) could be achieved with little or no incremental cost, assuming evolutionary improvements in renewable technologies.

There are significant inherent uncertainties with respect to future electricity demand, technology improvements, fossil energy prices, social and institutional choices, and regulatory and legislative actions related to the scenarios examined that, in turn, contribute to significant uncertainty in the implications reported above. Further, there are a variety of indirect (or downstream) implications that may result from the direct electric sector cost, environmental, and social implications identified. For example, incremental investment in generation capacity and associated infrastructure will have implications related to economic activity and employment in the energy industry. Reductions in fossil energy consumption will have environmental implications beyond air emissions, including implications related to water quality, terrestrial and marine contamination, and waste disposal, not only associated with electricity generation facilities but also for activities related to fuel extraction and transportation. Further, air emissions reductions will have implications for human health and climate change. Identification, and in some cases quantification, of these indirect implications is an active area of wide-ranging research. This analysis does not attempt to evaluate these indirect impacts of high renewable electricity futures. Further research is critically needed to systematically assess the relative impacts of different forms of energy supply in the context of a robust comprehensive framework that assesses both direct and indirect impacts. Such research could inform national energy policy decisions as well as local siting and permitting processes related to proposed generation facilities and supporting infrastructure.

Effects of Demand Growth on High Renewable Electricity Futures

With higher electricity demand growth, high levels of renewable generation present increased resource and grid integration challenges. RE Futures did not explicitly evaluate the cost effectiveness of energy efficiency adoption compared with supply-side options. However, the

[37] The RE-ETI assumptions are based on evolutionary improvements to currently commercial technologies and do not reflect DOE activities to further lower renewable technology costs so that they achieve parity with conventional technologies.

analysis suggests that under a high-demand scenario, greater and more rapid deployment of renewable and other supply- and demand-side technologies would be required. For example, while 32–46 GW/yr of renewable capacity additions were estimated from 2041 to 2050 in the low-demand core 80% RE scenarios, approximately 66 GW/yr would be needed during the same time period under a more-traditional, higher-demand trajectory. The analysis also found that in the 80%-by-2050 renewable electricity high-demand scenario, variable resources (wind and PV) were deployed to a greater extent in absolute and percentage terms than they were in the low-demand scenarios due to the greater resource available for wind and solar generation compared with other forms of renewable generation. As a consequence, additional flexible supply- and demand-side technologies, such as storage facilities, natural gas combustion turbine power plants, and interruptible load, were deployed and greater transmission expansion was needed to connect remotely located renewable resources of all types.

Higher end-use electricity demand increased the environmental impacts from the electric sector, such as greater greenhouse gas emissions, water use for thermoelectric cooling, and land use. In addition, higher demand growth also resulted in a greater increase in electricity prices. For example, in the High-Demand 80% RE scenario, the average annual retail electricity price increased by 1.3% per year (2011–2050, in real dollar terms) compared with 1.1% per year in the (low-demand) 80% RE-ITI scenario.[38] The increase in retail electricity prices driven by higher demand growth is not restricted to the high renewable penetration scenarios; it is evident under the baseline scenario as well. In particular, the average annual retail electricity price increased by 0.6% per year (2011–2050, in real dollar terms) in the High-Demand Baseline scenario compared with 0.3% per year in the Low-Demand Baseline scenario. While these results indicate that higher demand growth would lead to greater electricity price increases, they also demonstrate that the direct *incremental* costs associated with high renewable generation levels actually decreased under higher demand growth.

Conclusions

The RE Futures study assesses the extent to which future U.S. electricity demand could be supplied by commercially available renewable generation technologies—including wind, utility-scale and rooftop PV, CSP, hydropower, geothermal, and biomass—under a range of assumptions for generation technology improvement, electric system operational constraints, and electricity demand. Within the limits of the tools used and scenarios assessed, hourly simulation analysis indicates that estimated U.S. electricity demand in 2050 could be met with 80% of generation from renewable energy technologies with varying degrees of dispatchability together with a mix of flexible conventional generation and grid storage, additions of transmission, more responsive loads, and foreseeable changes in power system operations. While the analysis was based on detailed geospatially rich modeling down to the hourly timescale, the study is subject to many limitations both with respect to modeling capabilities and the many assumptions required about inherently uncertain variables, including future technological advances, institutional choices, and market conditions. Nonetheless, the analysis shows that realizing this significant transformation of the electricity sector would require:

[38] To isolate the effect of demand growth, the High-Demand 80% RE Scenario is compared with the 80% RE-ITI scenario since they both relied on the same technology improvement projection and used the same assumptions related to transmission, system flexibility, and renewable resources.

- Sustained build-up of many renewable resources in all regions of the United States
- Deployment of an appropriate mix of renewable technologies from the abundant and diverse U.S. renewable resource supply in a way that accommodates institutional or operational constraints to the electricity system, including constraints to transmission expansion, system flexibility, and resource accessibility
- Establishment of mechanisms to ensure adequate contribution to planning and operating reserves from conventional generators, dispatchable renewable generators, storage, and demand-side technologies
- Increasing the flexibility of the electric system through the adoption of some combination of storage technologies, demand-side options, ramping of conventional generation, more flexible dispatch of conventional generators, energy curtailment, and transmission
- Expansion of transmission infrastructure to enable access to diverse and remote resources and greater reserve sharing and balancing over larger geographic areas.

These general requirements indicate that many aspects of the electric system may need to evolve substantially for high levels of renewable electricity to be deployed. Significant further work is needed to improve the understanding of this potential evolution, such as the following:

- A comprehensive cost-benefit analysis to better understand the economic and environmental implications of high renewable electricity futures relative to today's electricity system largely based on conventional technologies and alternative futures in which other sources of clean energy are deployed at scale
- Further investigation of the more complete set of issues around all aspects of power system reliability because RE Futures only partially explores the implications of high penetrations of renewable energy for system reliability
- Improved understanding of the institutional challenges associated with the integration of high levels of renewable electricity, including development of market mechanisms that enable the emergence of flexible technology solutions and mitigate market risks for a range of stakeholders, including project developers
- Analysis of the role and implications of energy research and development activities in accelerating technology advancements and in broadening the portfolio of economically viable future renewable energy supply options and supply- and demand-side flexibility tools.

Appendix. Project Participants and Contributors

The National Renewable Energy Laboratory coordinated preparation of the RE Futures report, which is the culmination of contributions from more than 110 individuals and more than 35 organizations representing industry, utilities, universities, electric system operators and transmission organization, energy regulators, the government, and other sectors. The Project Leaders regret the inadvertent omission of any project participants and contributors, whether their input to the project involved contributing to project design, conducting analysis, authoring or contributing content, reviewing manuscript drafts, or producing the report.

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References

Black & Veatch. (2012). *Cost and Performance Data for Power Generation Technologies*. Overland Park, KS: Black & Veatch.

DOE. (2011). *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge, TN: ORNL.

EIA. (2009). *Energy Market and Economic Impacts of HR 2454, the American Clean Energy and Security Act of 2009*. SR-OIAF/2009-05. Washington, DC: U.S. Energy Information Administration. http://www.eia.doe.gov/oiaf/servicerpt/hr2454/. Accessed January 26, 2012.

EIA. (2010). *Energy Market and Economic Impacts of the American Power Act of 2010*. SR-OIAF/2010-01.Washington, DC: U.S. EIA. http://www.eia.doe.gov/oiaf/servicerpt/kgl/. Accessed January 27, 2012.

EIA. (2011a). "Analysis of Impacts of a Clean Energy Standard as Requested by Chairman Bingaman." Analysis and Projections. http://www.eia.gov/analysis/requests/ces_bingaman/.

EIA. (2011b). "Analysis of Impacts of a Clean Energy Standard as Requested by Chairman Hall." Analysis and Projections. http://www.eia.gov/analysis/requests/ces_hall/.

EPA (U.S. Environmental Protection Agency). (2009). "EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress." Washington, DC: EPA Office of Atmospheric Programs. http://www.epa.gov/climatechange/economics/pdfs/HR2454_Analysis.pdf. Accessed January 27, 2012.

EPA. (2010). "EPA Analysis of the American Power Act in the 111th Congress." Washington, DC: EPA Office of Atmospheric Programs. http://www.epa.gov/climatechange/economics/pdfs/EPA_APA_Analysis_6-14-10.pdf. Accessed January 27, 2012.

Pfeifenberger, J.; Fox-Penner, P.; Hou, D. (2009). "Transmission Investment Needs and Cost Allocation: New Challenges and Models." http://www.brattle.com/_documents/UploadLibrary/Upload823.pdf. Accessed January 27, 2010.

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