ES.3.5 Impacts Specific to Offshore and Distributed Wind

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

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

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

ES.4 The Wind Vision Roadmap: A Pathway Forward

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

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

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

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

ES.4.1 Core Roadmap Actions

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

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

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

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

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

Table ES.4-1. Roadmap Strategic Approach

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

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

Text Box ES-1.

High-Level Wind Vision Roadmap Actions

1 Wind Power Resources and Site Characterization

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

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

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

2 Wind Plant Technology Advancement

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

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

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

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

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

3 Supply Chain, Manufacturing and Logistics

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

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

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

4 Wind Power Performance, Reliability, and Safety

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

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

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

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

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

Continues next page

Text Box ES-1. *(Continued)*

High-Level Wind Vision Roadmap Actions

5 Wind Electricity Delivery and Integration

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

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

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

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

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

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

6 Wind Siting and Permitting

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

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

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

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

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

7 Collaboration, Education, and Outreach

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

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

8 Workforce Development

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

9 Policy Analysis

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

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

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

ES.4.2 Risk of Inaction

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

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

ES.5 Conclusions

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

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

ES.5.1 The Opportunity

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

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

ES.5.2 The Challenge

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

ES.5.3 Moving Forward

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

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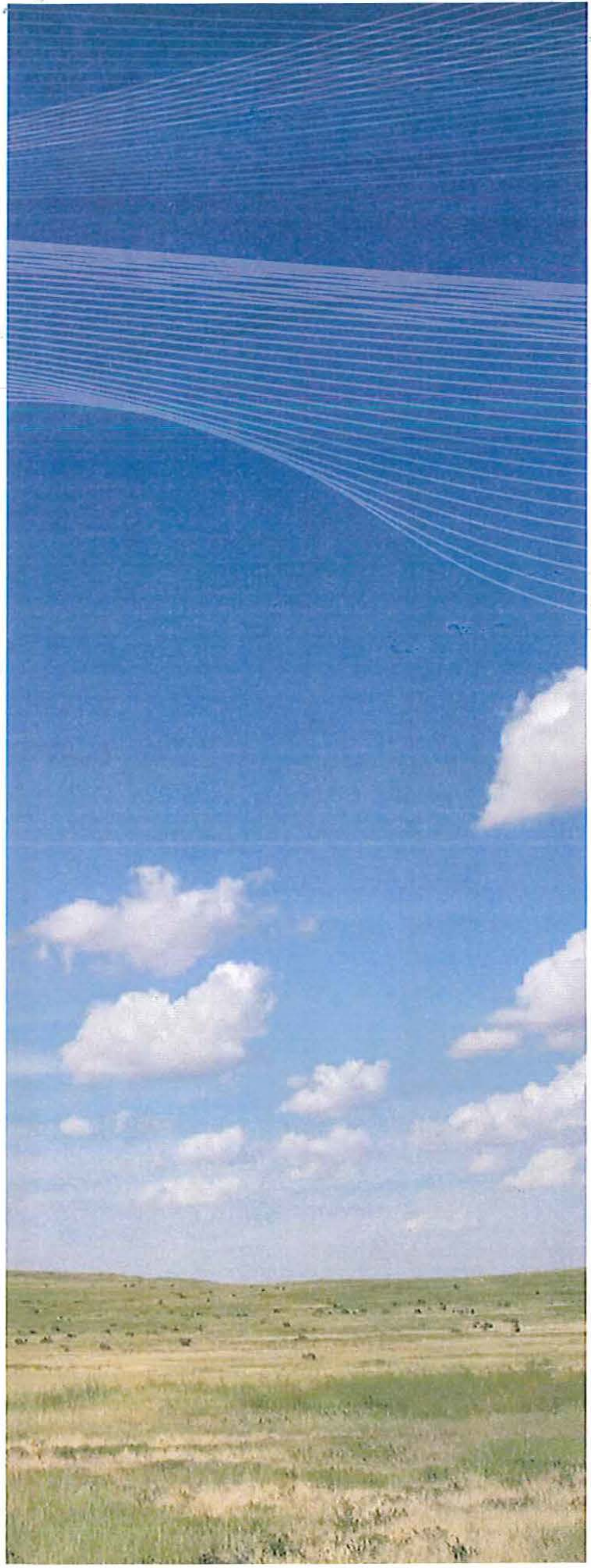


1 Introduction to the *Wind Vision*

Summary

The *Wind Vision* consists of four components:

1 **Documentation of the current state of wind power in the United States and identification of key accomplishments and trends over the decade leading up to 2014 (Chapter 2);**

2 **Exploration of the potential for wind power to contribute to the future electricity needs of the nation, including objectives such as reduced carbon emissions, improved air quality, and reduced water use (Chapter 3);**

3 **Quantification of costs, benefits, and other impacts associated with continued deployment and growth of U.S. wind power (Chapter 3); and**

4 **Identification of actions and future achievements that could support continued growth in the use and application of wind-generated electricity (Chapter 4).**

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

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

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

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

Analytical Framework of the *Wind Vision*

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

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

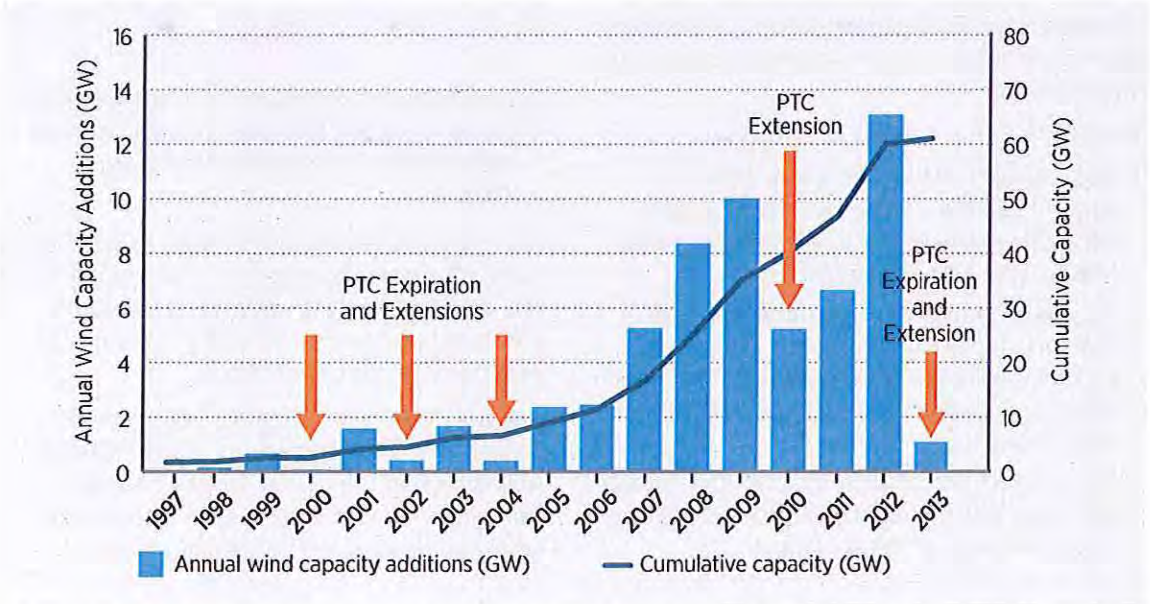
1.0 *Wind Vision*—Historical Context

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

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

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

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



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

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

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

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

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

The *Wind Vision* consists of four components:

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

Text Box 1-1.

Snapshot of the Wind Business in 2013

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

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

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

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

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

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

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

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

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

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

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

1.1 Key Trends Motivating the *Wind Vision*

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

1.1.1 Wind Business Evolution

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

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

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

1.1.2 Electric Sector Evolution

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

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

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

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

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

Table 1-1. Trends in Global Wind Capacity Additions

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

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

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

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

1.1.3 Wind Manufacturing Sector Impacts

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

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

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

1.1.4 Economic and Environmental Impacts

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

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

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

Text Box 1-2.

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

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

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

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

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

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

1.2 Understanding the Future Potential for Wind Power

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

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

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

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

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

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

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

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

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

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

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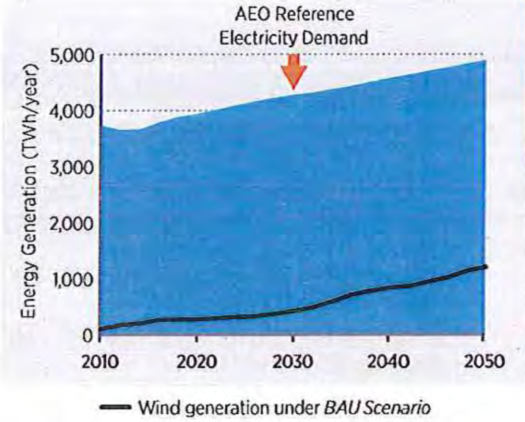
[6] ReEDS analysis scenarios represent economically optimal futures as determined by the ReEDs decision framework. Although these scenarios are not intended to be market projections or predictions of future wind deployment, they do provide insight into the potential for wind as a function of current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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

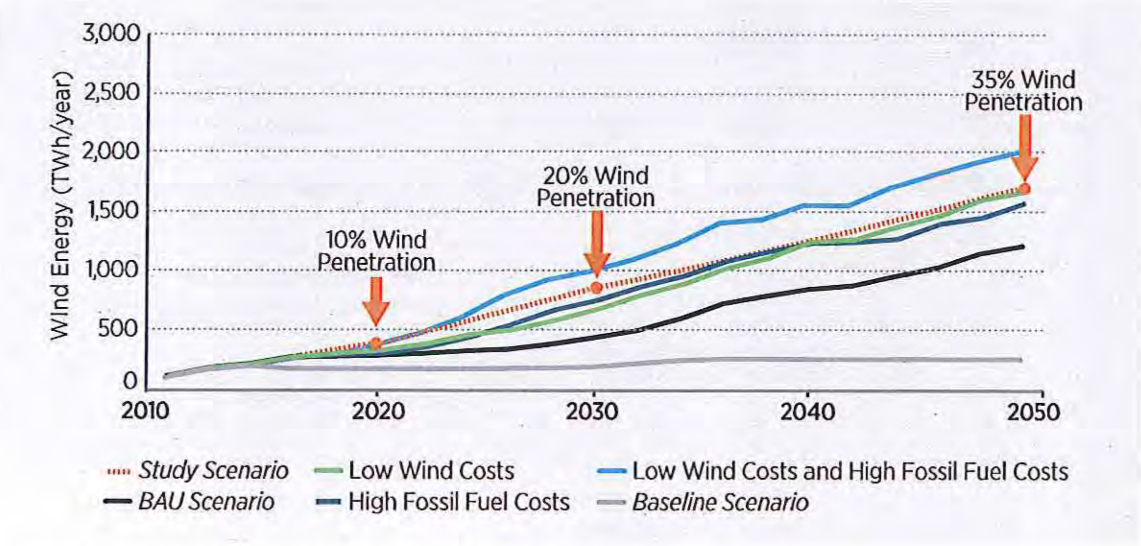
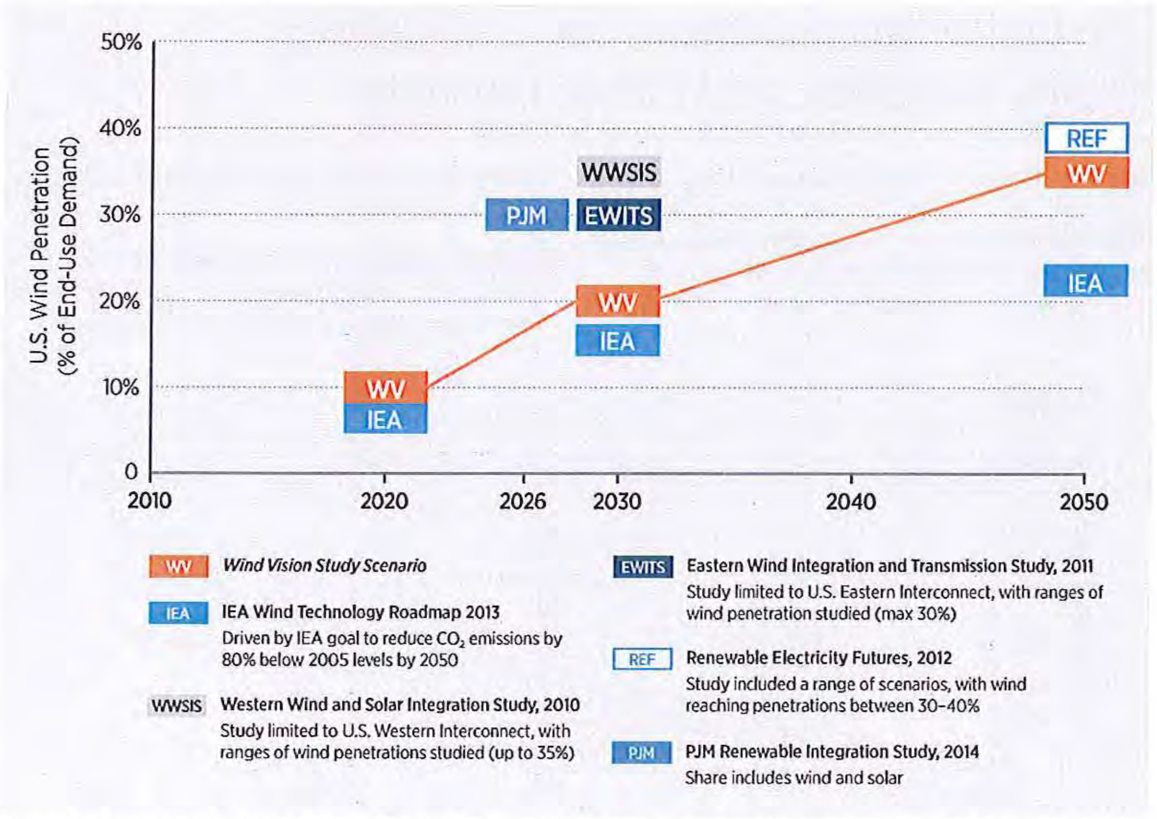


Figure 1-4. *Wind Vision Study Scenario* relative to *BAU Scenario* and Sensitivities

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

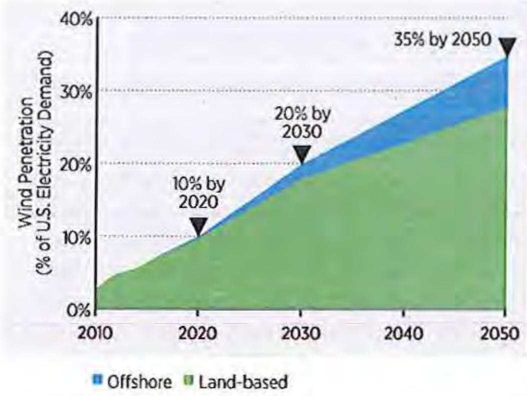
The positioning of the *Study Scenario* relative to the *BAU* results and a sub-sample of the sensitivities that entail aggressive wind cost reductions, high fossil fuel costs, or a combination of these two variables is shown in Figure 1-4. These data demonstrate that the *Study Scenario* falls within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

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



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

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



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

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

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

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

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

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

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

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

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

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

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

1.4 Project Implementation

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

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

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

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

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

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

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

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

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

1.5 Report Organization

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

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

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

Chapter 1 References

[1] *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*. U.S. Department of Energy. Washington, DC: DOE, 2008. Accessed Dec. 13, 2014: *http://energy.gov/eere/wind/20-wind-energy-2030-increasing-wind-energys-contribution-us-electricity-supply*.

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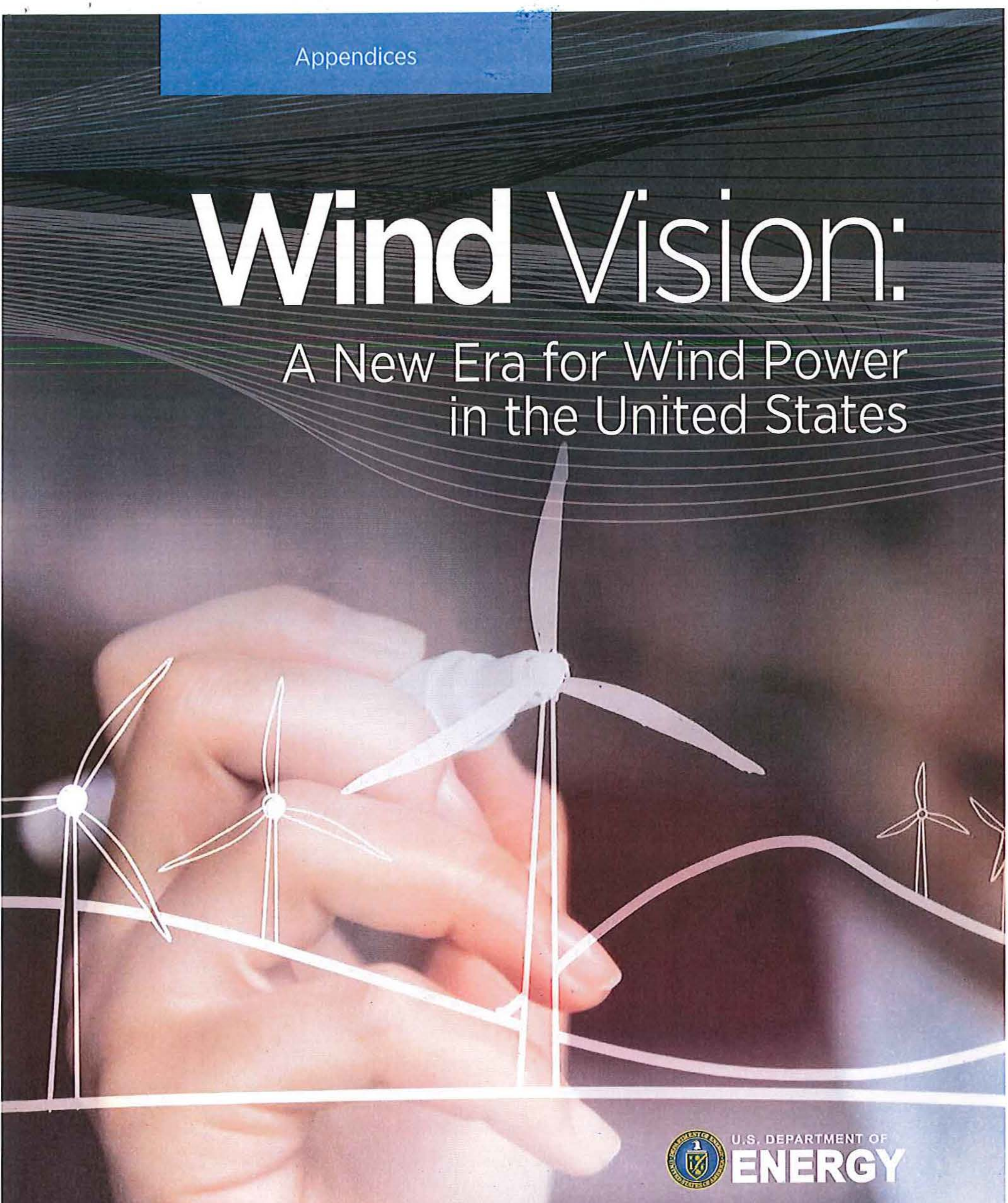
Appendices

Wind Vision:

A New Era for Wind Power in the United States



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Appendix G: Regional Energy Deployment System (ReEDS) Model—Additional Inputs and Assumptions

Chapter 3 provides a summary of the Regional Energy Deployment System (ReEDS) model and input assumptions. This appendix accompanies that chapter by providing more details about the model and the non-wind technology cost and performance assumptions. In particular, this appendix includes a description of the ReEDS model representation and data sources, and numerical values of key input assumptions used to develop the scenarios contained in the *Wind Vision* analysis.

The appendix is organized as follows:

- An overview of the ReEDS model and list of references to model documentation and other recent studies (Section G.1)
- The cost and performance assumptions of the non-wind generation technologies (Section G.2)
- Fuel price formulations and assumptions (Section G.3)
- Retirement assumptions (Section G.4)
- Financing parameters used in ReEDS investment and dispatch decisions (Section G.5)
- Electricity demand assumptions (Section G.6)
- Transmission cost and modeling assumptions (Section G.7).

Notably, the assumptions for wind technologies and resource are described in Appendix H.

G.1 ReEDS Model

The primary analytic tool used for this analysis is the ReEDS electric sector capacity expansion model [1]. ReEDS is a capacity expansion model that simulates the construction and operation of generation and transmission capacity to meet electricity demand. The model relies on system-wide, least-cost optimization to provide estimates of the type and location of fossil, nuclear, renewable, and storage resource development; the transmission infrastructure expansion requirements of those installations; and the generator dispatch and fuel needed to satisfy regional demand requirements and maintain grid system adequacy. The model also considers technology, resource, and policy constraints; including state renewable portfolio standards. ReEDS models scenarios of the continental U.S. electricity system in 2-year solve-periods out to 2050. In the *Wind Vision* analysis, ReEDS is used to analyze potential changes in the generation mix of the electricity sector under certain conditions and to generate a set of future scenarios for the U.S. electricity sector from which the impacts of a high penetration wind future are assessed. Although ReEDS scenarios are not forecasts or projections, they provide a common framework for understanding the incremental effects associated with specific power sector changes, such as those prescribed in the *Study Scenario*.

ReEDS is specifically designed to represent the unique characteristics of renewable generation, including wind—variability, uncertainty, geographic resource constraints, and transmission—and to assess its impacts on the broader electric system. Its high spatial resolution and statistical treatment of the impact of variable wind and solar resources enable representation of the relative value of geographically and temporally constrained renewable power resources. In ReEDS, the continental United States is divided into 356 wind/concentrating solar power (CSP) resource regions and 134 model balancing areas (BAs).[1] The resource regions are where wind (and CSP) resource availability and quality are evaluated and wind capacity expansion is modeled. The 134 BAs are where all other generation technologies are deployed in the model, and where electricity demand and reserves need to be met. Long-distance transmission is represented between adjacent BAs.

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[1] While the boundaries of real balancing authority areas helped to inform the design of the model BAs, the ReEDS BAs do not correspond perfectly with real balancing authority areas, where boundaries are dynamic and likely to change in the future.

ReEDS also uses a supply curve for resource capacity versus infrastructure investment costs to model the intra-BA, spur-line costs required to interconnect wind (and CSP) capacity from its region to the transmission grid. Capturing the resource cost and quality at such a high geographical granularity enables ReEDS to find the lowest-cost renewable resource expansions by interconnecting high-quality resources through appropriate long-distance inter-BA transmission and intra-BA spur-line expansions.

There are also larger sets of regions within ReEDS: 48 states, 18 curtailment regions designed loosely after existing regional transmission operator and other reliability regions [2], 13 North American Electric Reliability Corporation (NERC) regions [3], and the three major interconnections—Western, Eastern, and Electric Reliability Council of Texas. The NERC regions are used to model inputs, such as load growth and fuel prices from the EIA and the National Energy Modeling System.

ReEDS dispatches all generation using multiple time slices to capture seasonal and diurnal demand and renewable generation profiles. In particular, each of the "solve years" from 2010 to 2050 is divided into 17 time slices that represent four diurnal time slices (morning, afternoon, evening, night) for each of the four seasons (winter, spring, summer, fall), and a summer peaking time slice (representing the top 40 hours of summer load). While this model time resolution allows the model to capture seasonal and diurnal variations in demand and wind profiles, it is insufficient to capture some of the shorter timescale phenomena associated with high, variable generation penetration and address the related challenges. To bolster how renewable grid integration might affect investment and dispatch decisions, the ReEDS model includes statistical parameters to address the variability and uncertainty of wind and certain other renewable resources. These parameters include capacity value for planning reserves, forecast error reserves, and curtailment estimates [1].

In addition to modeling wind—land-based and offshore—technologies, ReEDS includes a full suite of major generation and storage technologies, including coal-fired, natural gas-fired, oil and gas steam, nuclear, biopower, geothermal, hydropower, utility-scale solar, pumped-hydropower storage, compressed-air energy storage, and batteries[2]. To determine competition between the many electricity generation, storage, and transmission options throughout the contiguous United States, ReEDS chooses the cost-optimal mix of technologies that meet all regional electric power demand requirements, based on grid reliability (reserve) requirements, technology resource constraints, and policy constraints. This cost minimization routine is performed for each of 21 two-year periods from 2010 to 2050.

The major outputs of ReEDS include the amount of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric sector costs, electricity price, fuel demand and prices, and direct-combustion carbon dioxide emissions. Through these output metrics, ReEDS is able to provide estimates of the nationwide impact of higher wind penetration on the system over the coming decades. Greater detail for these model technology categories is provided in the next section. ReEDS applies standardized financing assumptions for investments in all technologies represented in the model (see section G.6). Annual electric loads and fuel price supply curves are exogenously specified to define the system boundaries for each period of the optimization, as discussed in latter sections.

The ReEDS documentation [1] provides a more detailed description of the model structure and equations. Recent publications using ReEDS include the SunShot Vision Study [4], the Renewable Electricity Futures study [5], other lab reports [6,7,8,9], and journal articles [10,11,12,13].[3] The ReEDS model was also used to develop scenarios for the 20% *Wind Energy by 2030* report [14].[4] The model documentation and more recent publications, however, describe a large number of model developments subsequent to that study. This appendix focuses on the primary

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2. Coal and natural gas with and without carbon capture and storage are included. ReEDS models natural gas combined cycle and combustion turbine technologies independently. Utility-scale solar includes photovoltaic and CSP with and without thermal energy storage; rooftop solar deployment is not modeled but applied as an exogenous input into the system. Section G.2 and Short et al. [1] describe the array of technologies modeled in ReEDS in greater detail.
3. See *www.nrel.gov/analysis/reeds* for a list of publications about and further description of ReEDS.
4. The version of the model used in the *20% Wind Energy by 2030* report [14] was referred to as the Wind Deployment System (WinDS) model; ReEDS reflects the current name of the model.

data assumptions and model representations that are used specifically for the *Wind Vision* analysis, which may differ from assumptions applied in prior studies using ReEDS.

While ReEDS represents many aspects of the U.S. electric system, it has certain key limitations. First, ReEDS is a system-wide optimization model and, therefore, does not consider revenue impacts for individual project developers, utilities, or other industry participants. Second, ReEDS does not explicitly model constraints associated with the manufacturing sector. All technologies are assumed to be available up to their technical resource potential. Third, technology cost reductions from manufacturing economies of scale and "learning by doing" are not endogenously modeled for this analysis; rather, current and future cost reduction trajectories are defined as inputs to the model (see also Appendix H). Fourth, with the exception of future fossil fuel prices, foresight is not explicitly considered in ReEDS (i.e., the model makes investment decisions based on current conditions, without consideration for how those conditions may evolve in the future). Furthermore, ReEDS is deterministic and has limited considerations for risk and uncertainty. Fifth, the optimization algorithm in ReEDS does not fully represent the prospecting, permitting, and siting hurdles that are faced by project developers for either electricity generation capacity or transmission infrastructure. Moreover, ReEDS does not include fuel infrastructure or land competition challenges associated with fossil fuel extraction and delivery. Finally, ReEDS models the power system of the continental United States and does not represent the broader United States or global energy economy. For example, competing uses of resources across sectors (e.g., natural gas) are not dynamically represented in ReEDS and end-use electricity demand is exogenously input to ReEDS for this study.

One consequence of these model limitations is that system expenditures estimated in ReEDS may be understated, as the practical realities associated with planning electric system investments and siting new generation and transmission facilities are not fully represented in the model. As wind technologies are expected to require new transmission infrastructure development and benefit from broad-based system coordination, this impact may be amplified when considering high wind penetration scenarios. At the same time, ReEDS' spatial resolution provides much more sophisticated evaluation of the relative economics among generation resources and significant incremental insight into key issues surrounding future wind deployment, including locations for future deployment, transmission expansion needs, impacts on planning and operating reserves, and wind curtailments.

With a system-wide optimization outlook, ReEDS is not designed to evaluate distributed generation scenarios. Accordingly, ReEDS analysis is supported by the Solar Deployment System (SolarDS) model [15]. SolarDS is used to generate a projection of rooftop solar photovoltaic (PV) deployment, which is then input into ReEDS. All ReEDS scenarios presented in this report rely on the same single rooftop PV capacity projection. The input parameters for SolarDS used in this analysis are similar to those used in the *SunShot Vision Study* [4] with some exceptions presented in section G.2. No other distributed generation technologies are modeled explicitly in the *Wind Vision*, although the unique impacts associated with distributed wind generation are discussed in Chapter 3.

G.2 Generator Assumptions—Technology Cost and Performance

ReEDS models a full suite of generation technologies, including renewable, non-renewable, and storage. The technologies modeled in ReEDS represent the existing capacity fleet as well as newer generation technologies that have not realized commercial deployment in the United States. With the exception of rooftop PV, the existing capacity in ReEDS only includes units that are primarily used to generate and transmit electricity to the grid and excludes facilities that generate electricity primarily for on-site consumption or combined heat and power facilities.[5] In addition, ReEDS does not allow capacity expansion for certain technology types due to the age of the technology or data limitations.

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[5] The treatment of rooftop PV is described in section G.2.2.

New capacity growth for the following technologies is allowed in ReEDS:

- Natural gas-fired combustion turbine (NGCT)
- Natural gas—combined cycle (NGCC)
- Natural gas with carbon capture and storage (NGCCS)[6]
- Coal-pulverized[7]
- Coal-integrated gasification combined cycle (Coal-IGCC)
- Coal with carbon capture and storage (Coal-CCS)[8]
- Nuclear
- Biopower
- Cofired coal and biomass[9]
- Utility-scale solar PV[10]
- Wind (land-based and offshore)
- CSP with and without thermal energy storage (TES)[11]
- Hydropower[12]
- Geothermal[13]

The following technologies are also modeled in ReEDS but new capacity additions are not allowed for:

- Old coal (with and without scrubbers)[14]
- Landfill gas and municipal solid waste[15]
- Oil and gas steam

In addition to the previously listed technologies, new rooftop PV capacity is exogenously included (see section G.2.2). ReEDS also models three separate energy storage technologies: pumped hydropower storage, batteries, and compressed air energy storage. The assumed resource, cost, and performance projections for these storage options are based on those modeled in the Renewable Electricity Futures study [16].

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[6] While CCS technologies are included in the ReEDS model and allowed to be built, none of the modeled scenarios in this report resulted in the deployment of CCS capacity

[7] New coal plants are assumed to have scrubbers. Coal plants that existed before 2010 are included in ReEDS and separated into three categories: new coal, old coal without scrubbers, and old coal with scrubbers. Old coal with and without scrubbers comprise plants built pre-1995. For the reported coal capacity and generation in Chapter 3, all coal technologies are aggregated together (new and old coal, coal-IGCC, and coal-CCS).

[8] Coal with CCS reflects IGCC coal technologies.

[9] Cofired plants represent new plants that can accommodate coal and biomass fuels, and retrofits to existing coal plants. In ReEDS, no more than 15% of the capacity of a cofired coal plant can operate on biomass feedstocks at any time. In Chapter 3, cofired capacity is separated into coal and biomass categories in the reported capacity and generation values. More particularly, the reported cofired coal capacity is split between coal and biomass (85% of the capacity included with coal and 15% included with biomass). The generation from cofired plants is split by the generation from each fuel in the modeled plants with energy from biomass feedstocks included in the biomass category.

[10] The cost and performance of utility-scale PV reflect 100-MW single-axis tracking systems.

[11] CSP without TES is represented by trough systems with a solar multiple of 1.4. CSP with TES includes trough and tower systems with a solar multiple of at least two and at least six hours of storage. ReEDS endogenously optimizes the system configuration of CSP with TES plants within these limits.

[12] Section G.2.3 discusses the hydropower resources modeled in ReEDS. No ocean or marine hydrokinetic technologies are included in ReEDS for the present analysis.

[13] Section G.2.4 discusses the geothermal resource modeled in ReEDS for the present analysis.

[14] Old coal represents facilities installed before 1995 and active as of the model start year (2010). A retrofit option is included in ReEDS to allow upgrades of coal capacity from the "without scrubber" category to the "with scrubber" category.

[15] In Chapter 3, landfill gas and municipal solid waste generation and capacity are included in the biomass values.

G.2.1 General Technology Assumptions

Each modeled technology is characterized by its regional resource potential, capital cost, operations and maintenance (O&M) costs, and heat rates or capacity factors. Other technology characteristics such as lifetime, reserve capability, and tax credits are also modeled as described in Short et al. [1]. Regional variations and adjustments in some of the technology characteristics are also included and described in the following sections and other ReEDS publications listed in section G.2. This section presents the capital, fixed O&M, variable O&M, and heat rates for all technologies modeled.

Cost and performance assumptions for all new conventional technologies and certain renewable technologies (e.g., biopower and geothermal) are largely based on projections from the EIA's Annual Energy Outlook (AEO) 2014 Reference scenario [17]. The modeling tool in the AEO 2014 endogenously models technology learning, wherein technology cost and performance parameters are informed by the amount of capacity deployed in a given scenario. As a result, the technology cost assumptions reflect the learning estimated in the AEO 2014 Reference scenario and are directly applied in ReEDS. ReEDS does not include any explicit representation of technology learning in the *Wind Vision* analysis. In addition, technology projections beyond 2040 are assumed to remain flat from the 2040 levels, as the AEO 2014 only includes data through 2040. For some technologies (e.g., hydropower), only O&M costs from the AEO 2014 Reference scenario are used, while capital costs are based on other data sources (see sections G.2.3 and G.2.4). Solar technology assumptions also diverge from the AEO and are described in section G.2.2. Assumptions for wind technologies and resource are described in Appendix H. Overnight capital, fixed O&M, and variable O&M cost projections are shown in Tables G-1, G-2, and G-3, respectively. Heat rate assumptions for new capacity are shown in Table G-4. All costs presented in this appendix are in real 2013 dollars unless otherwise noted.

Table G-1. Overnight Capital Cost Projections (2013$/Kilowatt [kW])

Generator	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydropower[a]	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**
NGCT	839	832	807	784	766	753	746	746	746
NGCC	988	1,010	954	931	912	899	889	889	889
NGCCS	NA	2134	1,967	1,883	1,806	1,746	1,695	1,695	1,695
Old coal with scrubbers	NA	NA	NA	NA	NA	NA	NA	NA	NA
Old coal without scrubbers	NA	NA	NA	NA	NA	NA	NA	NA	NA
New coal	2,988	3,389	3,284	3,218	3,157	3,105	3,060	3,060	3,060
Coal-IGCC	3,853	3,853	3,853	3,853	3,853	3,853	3,853	3,853	3,853
Coal-CCS	NA	6,478	6,218	6,008	5,803	5,630	5,465	5,465	5,465
Oil/gas steam	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nuclear	4,871	4,871	4,708	4,594	4,476	4,325	4,186	4,186	4,186

Table G-1. *(contd.)* Overnight Capital Cost Projections (2013$/Kilowatt [kW])

Generator	2010	2015	2020	2025	2030	2035	2040	2045	2050
Geothermal[b]	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**	**Supply curve**
Biopower[c]	4,188	4,188	3,651	3,587	3,520	3,451	3,363	3,363	3,363
Co-fire retrofit[d]	290	290	290	290	290	290	290	290	290
SO_2 scrubber retrofit[e]	536	536	536	536	536	536	536	536	536
Landfill gas	NA	NA	NA	NA	NA	NA	NA	NA	NA

a. Hydropower capital costs are represented through regional supply curves. No capital cost reductions are assumed for these technologies. See section G.2.3.

b. Geothermal capital costs are represented through regional supply curves. No capital cost reductions are assumed for these technologies. See section G.2.4.

c. The costs under the "biopower" category represent costs for new dedicated biopower plants.

d. The capital cost represents the cost to retrofit any existing coal facilities to be able to co-fire with biomass. Biomass co-firing is assumed to be limited to up to 15% of the total plant capacity. A plant that has been retrofitted to co-fire biomass is assumed to retain the existing heat rate and O&M costs of the original coal plant. ReEDS includes an option to deploy new facilities that can co-fire coal and biomass; however, none of the scenarios discussed in the *Wind Vision* analysis relied on this option.

e. Sulfur dioxide (SO_2) scrubber retrofits upgrade capacity from the "Old Coal without Scrubbers" category to the "Old Coal with Scrubbers" category.

Table G-2. Fixed O&M Costs for New and Existing Generators (2013$/kW-year)

Generator	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydropower	15.05	15.05	15.05	15.05	15.05	15.05	15.05	15.05	15.05
NGCT	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30
NGCC	14.48	14.48	14.48	14.48	14.48	14.48	14.48	14.48	14.48
NGCCS	NA	32.27	32.27	32.27	32.27	32.27	32.27	32.27	32.27
Old coal with scrubbers	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52
Old coal without scrubbers	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52
New coal	31.65	31.65	31.65	31.65	31.65	31.65	31.65	31.65	31.65
Coal-IGCC	52.16	52.16	52.16	52.16	52.16	52.16	52.16	52.16	52.16
Coal-CCS	NA	73.93	73.93	73.93	73.93	73.93	73.93	73.93	73.93
Oil/gas steam	27.44	27.44	27.44	27.44	27.44	27.44	27.44	27.44	27.44
Nuclear	94.68	94.68	94.68	94.68	94.68	94.68	94.68	94.68	94.68
Geothermal	114.61	114.61	114.61	114.61	114.61	114.61	114.61	114.61	114.61
Biopower	107.22	107.22	107.22	107.22	107.22	107.22	107.22	107.22	107.22
Co-fire retrofit[a]	see note	see note	see note	see note	see note	see note	see note	see note	see note
Landfill gas	398.70	398.70	398.70	398.70	398.70	398.70	398.70	398.70	398.70

e. A plant that has been retrofitted to co-fire biomass is assumed to retain the existing heat rate and O&M costs of the original coal plant.

Table G–3. Variable O&M Costs for New and Existing Generators (2013$/Megawatt-hour [MWh])

Generator	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydropower	2.69	2.69	2.69	2.69	2.69	2.69	2.69	2.69	2.69
NGCT	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10	13.10
NGCC	3.49	3.49	3.49	3.49	3.49	3.49	3.49	3.49	3.49
NGCCS	NA	6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88
Old with scrubbers	5.93	6.55	7.23	7.99	8.82	9.74	10.75	11.87	13.10
Old coal without scrubbers	5.93	6.55	7.23	7.99	8.82	9.74	10.75	11.87	13.10
New coal	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54
Coal-IGCC	7.33	7.33	7.33	7.33	7.33	7.33	7.33	7.33	7.33
Coal-CCS	NA	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58
Oil/gas steam turbines	4.19	4.62	5.11	5.64	6.22	6.87	7.59	8.38	9.25
Nuclear	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17
Geothermal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biopower	5.34	5.34	5.34	5.34	5.34	5.34	5.34	5.34	5.34
Cofire retrofit[a]	see note	see note	see note	see note	see note	see note	see note	see note	see note
Landfill gas	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88	8.88

[a] A plant that has been retrofitted to co-fire biomass is assumed to retain the existing heat rate and O&M costs of the original coal plant.

Table G-4. Heat Rates for New and Existing Generators (Million British Thermal Units [MMBtu]/MWh)

Generator	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydropower	NA	NA	NA	NA	NA	NA	NA	NA	NA
NGCT	10.28	10.02	9.76	9.50	9.50	9.50	9.50	9.50	9.50
NGCC	6.74	6.68	6.62	6.57	6.57	6.57	6.57	6.57	6.57
NGCCS	NA	7.51	7.50	7.49	7.49	7.49	7.49	7.49	7.49
Old Coal with Scrubbers	9.98	9.98	9.98	9.98	9.98	9.98	9.98	9.98	9.98
Old Coal without Scrubbers	10.26	10.26	10.26	10.26	10.26	10.26	10.26	10.26	10.26
New Coal	8.80	8.78	8.76	8.74	8.74	8.74	8.74	8.74	8.74
Coal-IGCC	8.70	8.28	7.87	7.45	7.45	7.45	7.45	7.45	7.45
Coal-CCS	NA	9.90	9.10	8.31	8.31	8.31	8.31	8.31	8.31
Oil/gas Steam	10.65	10.65	10.65	10.65	10.65	10.65	10.65	10.65	10.65
Nuclear	10.46	10.46	10.46	10.46	10.46	10.46	10.46	10.46	10.46
Geothermal	NA	NA	NA	NA	NA	NA	NA	NA	NA
Biopower	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50	13.50
Co-fire Retrofit[a]	see note	see note	see note	see note	see note	see note	see note	see note	see note
Landfill Gas	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00	18.00

a. A plant that has been retrofitted to co-fire biomass is assumed to retain the existing heat rate and O&M costs of the original coal plant.

G.2.2 Solar Technologies

The *Wind Vision* analysis includes three primary solar technologies: utility-scale PV, rooftop PV, and CSP. Solar power technology capital costs are benchmarked to cost data reported by Bolinger and Weaver [18] and GTM Research/Solar Energy Industries Association [19]. Capital cost projections from the base year to 2020 are aligned with the DOE 62.5% Reduction scenario (from 2010) documented in the *SunShot Vision Study* [4]. This cost trajectory was subsequently grounded against a sample of cost projections from the EIA [17], International Energy Agency [2,] Bloomberg New Energy Finance [20], Greenpeace/European Photovoltaic Industry Association [21], and GTM Research/Solar Energy Industries Association [19,22]. After 2020, costs decline linearly to reach the DOE 75% Reduction scenario [4] by 2040. Although literature estimates that emphasize this time period are fewer, this cost trajectory is also generally consistent with an average literature estimate [2,23,24]. Costs are assumed to be unchanged (in real terms) from 2040 to 2050.[16] Performance for all solar technologies varies regionally and is based on solar irradiance data from the National Solar Radiation Database.

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[16] Potential justifications for a flat cost over this time period include increasing uncertainty with time and diminishing returns from research and development investment.

Table G-5 presents the capital and O&M cost assumptions over the model horizon for utility-scale PV, which ReEDS models based on 100-megawatt (MW) single-axis tracking systems. Regional capacity factors are developed from the System Advisor Model's PV module [25] and range from 0.17 to 0.28.[17] The performance characteristics for ReEDS were developed using hourly weather data from the National Solar Radiation Database for 939 sites from 1998 to 2005. The representative PV capacity factor for each model BA reflects the site within each BA with the highest annual average capacity factor. No changes or improvements in capacity factor are assumed for utility-scale PV.

Table G-5. Technology Cost Assumptions for Utility-Scale PV (2013$)

Cost Type	2010	2013	2015	2020	2025	2030	2035	2040	2045	2050
Capital cost ($/kW$_{DC}$)	4,346	2,674	2,368	1,604	1,470	1,337	1,203	1,069	1,069	1,069
Fixed O&M ($/kW$_{DC}$-year)	21.73	18.47	16.30	7.61	7.61	7.61	7.61	7.61	7.61	7.61
Variable O&M ($/MWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Rooftop PV includes commercial and residential systems. The SolarDS model [15], a diffusion model for the continental U.S. rooftop market, is used to develop a future scenario for rooftop PV capacity. A single Rooftop PV scenario is exogenously defined for ReEDS and used across all scenarios in the *Wind Vision* analysis.

Similar to utility-scale PV, the cost assumptions used in the SolarDS modeling are based on the *SunShot Vision Study's* 62.5% and 75% solar cost reduction scenarios [4]. More specifically, the 62.5% cost reduction is reached in 2020 and the 75% cost reduction is reached in 2040.[18] Consistent with assumptions for all other technologies and policies, the current solar investment tax credit (ITC) trajectory is included in the SolarDS analysis. Specifically, a 30% ITC through 2016 dropping to 10% ITC after 2016 is included for all commercial systems.[19] All other assumptions are the same as those used in the *SunShot Vision Study* [4]. Figure G-1 shows the resulting capacity and generation trajectory for rooftop PV based on these assumptions and the SolarDS modeling. The rooftop PV trajectory shown in Figure G-1 includes 84 gigawatts (GW) by 2030 and 245 GW by 2050. Degradation of the efficiency of solar PV capacity over time is also modeled at 0.5% per year. This degradation is modeled by reducing the capacity of PV that generates energy by 0.5% per year.

The cost impacts of the scenarios presented in Chapter 3 exclude any costs associated with rooftop PV. Since the rooftop PV capacity trajectory is identical across all scenarios, essentially no impact on reported *incremental* costs of achieving the *Study Scenario* penetration levels is impacted by excluding costs associated with distributed generation. The only differences across scenarios associated with rooftop PV relate to rooftop PV curtailment estimates within ReEDS, which have only minor impacts. In addition, rooftop PV capital and O&M costs are excluded from ReEDS system expenditure estimates.

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[17] Capacity factors for utility-scale PV are based on the system capacity in watts direct current (W_{DC}) and generation in watts alternating current (W_{AC}). The capacity factor includes the conversion from DC to AC power.

[18] Similar to other solar technologies, rooftop PV capital costs are linearly interpolated between 2020 and 2040 and the capital costs are held constant at the 75% *SunShot Vision Study* cost reductions in all years after 2040.

[19] This assumption differs from the *SunShot Vision Study*, where the ITC was assumed to be eliminated after 2016.

The cost impacts of the scenarios presented in Chapter 3 exclude any costs associated with rooftop PV. Since the rooftop PV capacity trajectory is identical across all scenarios, essentially no impact on reported incremental costs of achieving the Study Scenario penetration levels is impacted by excluding costs associated with distributed generation. The only differences across scenarios associated with rooftop PV relate to rooftop PV curtailment estimates within ReEDS, which have only minor impacts. In addition, rooftop PV capital and O&M costs are excluded from ReEDS system expenditure estimates.

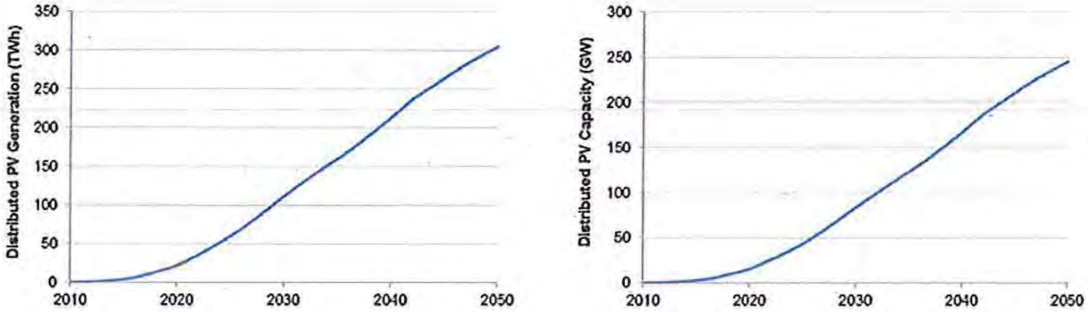

Figure G-1. Capacity GW and potential generation in terawatt-hours (TWh) of rooftop PV for all Study and Baseline Scenarios[20]

Consistent with assumptions around solar PV, assumptions for CSP with thermal energy storage (TES) costs are based on the 62.5% and 75% cost reduction scenarios from the SunShot Vision Study [4]. CSP capital costs are more complicated than other technologies because ReEDS optimizes the CSP system configuration through separate considerations for the turbine, solar field, and storage components of the system. Within its solutions, ReEDS can deploy CSP with TES plants with any configuration of solar multiples and storage capacity within certain limitations [4]. For example, the TES capacity must be between 6 and 12 hours of storage (rated at maximum power output), resulting in a capacity factor between 0.40 and 0.65. While future deployment of CSP systems will likely result in a range of technologies, the cost and performance assumptions in ReEDS assumes that trough systems are deployed prior to 2025 and power towers are deployed subsequently. Further details on CSP modeling in ReEDS can be found in the SunShot Vision Study [4].

Table G-6 shows the capital and O&M cost projections for CSP systems with six hours of TES and a solar multiple of two.[21]

Table G-6. Technology Cost Assumptions for CSP Systems with Six Hours of TES and a Solar Multiple of Two (2013$)

Cost Type	2010	2015	2020	2025	2030	2035	2040	2045	2050
Capital cost ($/kW)	6,780	6,780	4,072	3,824	3,576	3,328	3,080	3,080	3,080
Fixed O&M ($/kW-year)	84.98	67.98	50.99	50.99	50.99	50.99	50.99	50.99	50.99
Variable O&M ($/MWh)	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26

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[20] Potential generation does not remove curtailments, which are estimated internally by ReEDS. Curtailments for variable generation are removed in the generation reported in Chapter 3.

[21] Solar multiple is defined as the ratio of the solar field capacity to the power block.

Appendix H: *Wind Vision* Wind Power Technology Cost and Performance Assumptions

This appendix defines cost and performance assumptions for wind technology in the *Wind Vision* analysis. First, the landscape of current U.S. land-based and offshore wind (OSW) technology costs is described. Second, the conversion of market-reported numbers to terms appropriate for use in the Regional Energy Deployment System (ReEDS) model is traced. Finally, the future wind cost reduction trajectories applied in the *Wind Vision* analysis are outlined. The scope of this appendix is utility-scale wind technology installations[1] in the United States. Scenarios analyzing the impact of changes expected in wind technology over the coming decades are discussed in Chapter 3 of the *Wind Vision* report. Actions that could assist in bringing about the cost reductions and performance improvements in these scenarios are highlighted in Chapter 4. Modeling assumptions for current and future costs of other power generation, transmission, and storage technologies are found in Chapter 3 and Appendix G.

The primary elements of this appendix are:

- A description of base-year technology cost and performance parameters
- A description of the methodology used to convert market data into a format that can be used as input to the ReEDS model
- A description of project-level costs to connect to the transmission grid (not including long-haul transmission costs that are "built" by the ReEDS model based on how a study scenario is developed)
- A table of the cost and performance parameters chosen as inputs to represent techno-resource groups (TRGs) in the ReEDS model
- A graphical representation of the elements that produce the total project costs as "seen" by ReEDS for all potential project sites
- A description of future wind power cost and performance characteristics applied in the *Wind Vision* analysis.

H.1 Overview

The ReEDS model represents a range of electricity generation technologies, including land-based and offshore wind technologies. This appendix describes the methods used to develop ReEDS inputs for wind power technologies, based on market data, geographic cost and performance variation, distance to existing transmission infrastructure, and project financing. To the extent possible, ReEDS model assumptions reflect the best available published representation of land-based and offshore wind plant costs, performance, and geographic variation for the base year (2012). In addition, projections of future capital cost, operating cost, and energy production through 2050 are based on published literature and industry perspectives, with the latter obtained through interviews and additional literature.

H.1.1 Development of the Wind Energy Supply Curve

The Wind Energy Supply Curve is a representation of the cost of energy at all potential wind plant sites in contiguous states at a single point or snapshot in time. Figure H-1 demonstrates the elements needed to represent wind technology as a Wind Energy Supply Curve: project financing, grid connection costs, and wind plant techno-economic cost and performance in the base year and future years. The starting points for ReEDS deployment decisions are the cost and performance parameters that go into the supply curve calculations. ReEDS capacity expansion and dispatch decision-making considers the present value of investments associated with adding and operating new generation capacity (considering transmission and operational integration)

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[1] Land-based and offshore. Distributed wind is not modeled in the *Wind Vision*.

H.1.3 Future Wind Plant Cost and Performance Assumptions

The projections of future wind plant cost and performance represent three levels of wind technology advancement through 2050. Grid connection costs and financing costs are assumed to remain unchanged during the scenario; only the wind plant capital cost, operating costs, and capacity factor are changed. Tables H-4 and H5 contains the ReEDS model input assumptions that represent the three technology advancement perspectives. As noted above, the ReEDS model requires overnight capital cost (OCC), excluding construction-period finance costs.

Table H-4. Land-Based Future Wind Plant Cost and Performance Assumptions

Land-Based Cost Component	TRG	2012	2014	2020	2030	2050
Overnight capital cost (2013$/kW)	1 Low Cost	1,537	1,641	1,388	1,281	1,268
	1 Mid Cost	1,537	1,641	1,571	1,518	1,512
	1 High Cost	1,537	1,641	1,641	1,641	1,641
	2 Low Cost	1,665	1,641	1,388	1,281	1,268
	2 Mid Cost	1,665	1,641	1,571	1,518	1,512
	2 High Cost	1,665	1,641	1,641	1,641	1,641
	3 Low Cost	1,784	1,729	1,487	1,399	1,389
	3 Mid Cost	1,784	1,729	1,674	1,630	1,625
	3 High Cost	1,784	1,729	1,729	1,729	1,729
	4 Low Cost	1,807	1,758	1,570	1,540	1,536
	4 Mid Cost	1,807	1,758	1,738	1,724	1,722
	4 High Cost	1,807	1,758	1,758	1,758	1,758
	5 Low Cost	1,807	1,758	1,570	1,540	1,536
	5 Mid Cost	1,807	1,758	1,738	1,724	1,722
	5 High Cost	1,807	1,758	1,758	1,758	1,758
Net capacity factor (%)	1 Low Cost	47%	51%	58%	61%	62%
	1 Mid Cost	47%	51%	54%	57%	60%
	1 High Cost	47%	51%	51%	51%	51%
	2 Low Cost	46%	47%	53%	56%	57%
	2 Mid Cost	46%	47%	49%	52%	55%
	2 High Cost	46%	47%	47%	47%	47%
	3 Low Cost	44%	44%	51%	54%	56%
	3 Mid Cost	44%	44%	47%	50%	53%
	3 High Cost	44%	44%	44%	44%	44%
	4 Low Cost	38%	38%	45%	50%	51%
	4 Mid Cost	38%	38%	41%	44%	47%
	4 High Cost	38%	38%	38%	38%	38%
	5 Low Cost	32%	32%	38%	42%	43%
	5 Mid Cost	32%	32%	35%	37%	40%
	5 High Cost	32%	32%	32%	32%	32%

Land-Based Cost Component	TRG	2012	2014	2020	2030	2050
OPEX (2013$/kW/year)	Low Cost	51	51	47	43	39
	Mid Cost	51	51	49	47	46
	High Cost	51	51	51	51	51

Table H-5. Offshore Future Wind Plant Cost and Performance Assumptions

Offshore Cost Component	TRG	2014	2016	2020	2023[a]	2030	2050
Overnight capital cost (2013$/kW)[b]	1 Low Cost	5,307	4,683	4,111	3,591	3,227	2,733
	1 Mid Cost	5,307	5,080	4,527	4,007	3,851	3,629
	1 High Cost	5,307	5,522	5,099	4,735	4,735	4,735
	2 Low Cost	5,307	4,683	4,111	3,591	3,227	2,733
	2 Mid Cost	5,307	5,080	4,527	4,007	3,851	3,629
	2 High Cost	5,307	5,522	5,099	4,735	4,735	4,735
	3 Low Cost	5,307	4,683	4,111	3,591	3,227	2,733
	3 Mid Cost	5,307	5,080	4,527	4,007	3,851	3,629
	3 High Cost	5,307	5,522	5,099	4,735	4,735	4,735
	4 Low Cost	5,307	4,683	4,111	3,591	3,227	2,733
	4 Mid Cost	5,307	5,080	4,527	4,007	3,851	3,629
	4 High Cost	5,307	5,522	5,099	4,735	4,735	4,735
	5 Low Cost	5,860	5,170	4,537	3,961	3,559	3,012
	5 Mid Cost	5,860	5,613	4,997	4,422	4,249	4,003
	5 High Cost	5,860	6,092	5,630	5,227	5,227	5,227
	6 Low Cost	5,860	5,170	4,537	3,961	3,559	3,012
	6 Mid Cost	5,860	5,613	4,997	4,422	4,249	4,003
	6 High Cost	5,860	6,092	5,630	5,227	5,227	5,227
	7 Low Cost	5,860	5,170	4,537	3,961	3,559	3,012
	7 Mid Cost	5,860	5,613	4,997	4,422	4,249	4,003
	7 High Cost	5,860	6,092	5,630	5,227	5,227	5,227
	8 Low Cost	6,859	6,049	5,306	4,631	4,158	3,517
	8 Mid Cost	6,859	6,571	5,846	5,171	4,969	4,680

Offshore Cost Component	TRG	2014	2016	2020	2023[a]	2030	2050
Overnight capital cost (2013$/kW)[b]	8 High Cost	6,859	7,132	6,589	6,117	6,117	6,117
	9 Low Cost	6,859	6,049	5,306	4,631	4,158	3,517
	9 Mid Cost	6,859	6,571	5,846	5,171	4,969	4,680
	9 High Cost	6,859	7,132	6,589	6,117	6,117	6,117
	10 Low Cost	6,859	6,049	5,306	4,631	4,158	3,517
	10 Mid Cost	6,859	6,571	5,846	5,171	4,969	4,680
	10 High Cost	6,859	7,132	6,589	6,117	6,117	6,117
Net Capacity Factor	1 Low Cost	47%	48%	49%	53%	54%	55%
	1 Mid Cost	47%	47%	49%	52%	52%	53%
	1 High Cost	47%	47%	48%	52%	52%	52%
	2 Low Cost	44%	44%	45%	49%	49%	50%
	2 Mid Cost	43%	43%	44%	47%	48%	49%
	2 High Cost	44%	43%	44%	47%	47%	47%
	3 Low Cost	40%	40%	41%	45%	45%	46%
	3 Mid Cost	40%	40%	41%	43%	44%	45%
	3 High Cost	40%	40%	40%	43%	43%	43%
	4 Low Cost	34%	34%	35%	38%	38%	39%
	4 Mid Cost	34%	34%	35%	37%	37%	38%
	4 High Cost	34%	34%	34%	37%	37%	37%
	5 Low Cost	47%	47%	48%	53%	53%	54%
	5 Mid Cost	47%	47%	48%	51%	51%	53%
	5 High Cost	47%	47%	47%	51%	51%	51%
	6 Low Cost	44%	44%	45%	49%	50%	51%
	6 Mid Cost	44%	44%	45%	48%	48%	49%
	6 High Cost	44%	44%	44%	48%	48%	48%
	7 Low Cost	42%	42%	43%	47%	47%	48%
	7 Mid Cost	42%	42%	43%	46%	46%	47%
	7 High Cost	42%	42%	42%	46%	46%	46%

Offshore Cost Component	TRG	2014	2016	2020	2023[a]	2030	2050
Net Capacity Factor	8 Low Cost	49%	49%	51%	55%	56%	57%
	8 Mid Cost	49%	49%	51%	54%	54%	55%
	8 High Cost	49%	49%	50%	54%	54%	54%
	9 Low Cost	47%	47%	48%	53%	53%	54%
	9 Mid Cost	47%	47%	48%	51%	51%	53%
	9 High Cost	47%	47%	47%	51%	51%	51%
	10 Low Cost	44%	44%	45%	49%	49%	50%
	10 Mid Cost	44%	44%	45%	47%	48%	49%
	10 High Cost	44%	44%	44%	47%	48%	48%
OPEX (2013$/kW/year)	Shallow and Mid Low Cost	132	121	111	106	99	92
	Shallow And Mid Mid Cost	132	129	115	107	102	99
	Shallow and Mid High Cost	132	132	121	119	119	119
	Deep Low Cost	162	149	136	130	122	114
	Deep Mid Cost	162	159	141	131	125	122
	Deep High Cost	162	162	149	146	146	146

[a] This year is included because several of the cost reduction trajectories in the literature describe cost reductions for offshore wind through 2023.

[b] Grid connection cost is not included in this table. To duplicate LCOE values in Table H-1 and Figure H-4, an additional $243/kW representing 30 km distance from shore must be added to the overnight capital cost.

H.2 Base-Year Wind Plant Techno-Economic Cost and Performance Parameters

H.2.1 Introduction

In order to provide the most representative cost and performance inputs for ReEDS base year modeling, the analysis estimated cost and performance parameters for current technology, and matched technology with resource (for land-based wind plants) or resource and water depth (for offshore wind plants). An LCOE was calculated for each potential wind plant site, including operations and financing cost; sites were grouped by cost; and the capacity-weighted average for each group was calculated. Adjustments were then made to make the numbers compatible with the ReEDS model format.

H.2.2 AWS Truepower Wind Resource Data

Figure H-5 illustrates the process by which the analysis made the wind resource data usable in the model. The wind resource data used for this study were developed for the National Renewable Energy Laboratory (NREL) by AWS Truepower (AWST). These specific site data include a typical meteorological year of simulated hourly

Appendix N: Contributors

The U.S. Department of Energy (DOE) acknowledges the authors, reviewers, and various contributors listed below, each of whom contributed to this report. The DOE Wind and Water Power Technologies Office (WWPTO) managed the project in collaboration with the American Wind Energy Association and the Wind Energy Foundation. These three organizations solicited the participation of the wind industry and other expertise. Expert input for the project was provided by members of 11 Task Forces, a Senior Peer Review Group, and an External Review Group comprising senior managers from wind, electric power, non-governmental organizations, and government organizations involved with wind power and the energy and electricity sectors. Overall project coordination was carried out by DOE.

This technical report is the culmination since May 2013 of contributions from more than 250 individuals and more than 100 organizations representing DOE, the wind industry, the electric power sector, environmental stewardship organizations, and four major national laboratories (Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories). Contributions and support from these participants were important throughout the development of this report.

Various offices within DOE and other federal agencies also provided counsel and review throughout the effort. The DOE Office of Energy Efficiency and Renewable Energy was a principal internal adviser. DOE's Office of Energy Policy and Systems Analysis and Office of Electricity Delivery and Energy Reliability also provided input. DOE WWPTO consulted with the other DOE energy program technology offices—including solar, geothermal, hydroelectric, fossil, and nuclear energy—and the U.S. Energy Information Administration to obtain the best available information on characteristics for those technologies. DOE WWPTO also coordinated with other federal agencies, such as the U.S. Department of the Interior's (DOI's) Bureau of Ocean Energy Management and the National Oceanic and Atmospheric Administration (NOAA). Eleven task forces conducted analyses, prepared sections of this report, and provided valuable guidance during the final review processes. Lead authors and main advisors for each chapter are shown in **bold**.

The final version of this document was prepared by the U.S. Department of Energy.

Overall Direction

Wind Vision Project Management

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