Wind Vision: A New Era for Wind Power in the United States

Despite near- to medium-term cost barriers, a future U.S. electricity system in which wind plays a major role is technically feasible; could result in enduring benefits globally, nationally, and locally; and could result in consumer and system cost savings in the long term.

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I. Introduction

Wind power is one of the fastest-growing sources of new electricity supply and the largest source of new renewable power generation added in the United States since 2000. Wind power has abundant resource potential; competitive, long-term, stable pricing; and favorable environmental attributes. At the same time, low natural gas prices, low wholesale electricity prices, and low electricity demand growth since 2008 are impacting investments for all new electric generation. Annual U.S. wind capacity additions have varied dramatically owing to these factors as well as trends in wind power costs and federal and state policy.

In this context, the U.S. Department of Energy (DOE) initiated the *Wind Vision* study to inform a broad range of stakeholders about wind power's potential and to quantify the costs and benefits of continued wind investments (DOE, 2015). The study evaluates an ambitious but credible scenario in which wind energy serves 10 percent of the nation's end-use electricity demand by 2020, 20 percent by

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2030, and 35 percent by 2050. This scenario is not a prediction but a framework for evaluating the impacts of expanded wind deployment. The *Wind Vision* study updates and elaborates on an earlier DOE report, *20% Wind Energy by 2030* (DOE, 2008).

The *Wind Vision* study resulted from a collaborative effort. Under the leadership of the Wind and Water Power Technologies Office in DOE's Office of Energy Efficiency and Renewable Energy, the study drew on a diverse group of more than 250 energy experts, including representatives from grid operators, the wind industry, science-based organizations, academia, governmental agencies, national laboratories, and environmental-stewardship organizations. This ensures that the *Wind Vision* analysis, modeling inputs, and conclusions are based on the best available information from the fields of science, technology, economics, finance, and engineering.

This article highlights key findings and conclusions from the *Wind Vision* study. After describing recent progress and trends in the U.S. wind industry, it introduces the analytical scenarios and sums up the impacts of achieving the *Vision* scenario. The final sections summarize a roadmap for continued wind growth and offer conclusions about the opportunities and challenges associated with U.S. wind power.

II. U.S. Wind Industry Progress and Trends

At the end of 2013, U.S. wind capacity totaled more than 61 GW across 39 states, and wind supplied 4.5 percent of the nation's electricity demand—a significant expansion since 2008, when wind met 1.5 percent of U.S. demand (EIA, 2014a). Annual deployment increased from 2 GW in 2006, to 8 GW in 2008, to peak annual installations of 13 GW in 2012. Large amounts of wind power have been reliably integrated into electric power systems. Two states, Iowa and South Dakota, exceeded 25 percent of in-state generation from wind in 2013, and seven other states operated with greater than 12 percent of their generation from wind (AWEA, 2014a). Power system operators experienced with wind now view its use routinely as a dependable component in the portfolio of generating options.

Two states, Iowa and South Dakota, exceeded 25 percent of in-state generation from wind in 2013.

Technological advancements and declining wind power costs have facilitated this recent growth. The levelized cost of energy (LCOE) from wind in good to excellent resource sites declined by more than one-third from 2008 to 2013, from $71/megawatt-hour (MWh) to $45/MWh, and recent long-term power purchase agreements for wind energy have (with the benefit of federal tax incentives) regularly been signed at just $20–25/MWh (Wiser and Bolinger, 2014).[1] In some regions, especially with federal tax incentives, wind power prices are competitive with wholesale power prices and other sources of generation. Continued advancements and scale-up of turbine technology, such as longer blades and taller towers, have helped reduce wind power costs and enable broader geographic deployment.

The U.S. supply chain has grown to meet the increased demand for wind power. New investments in U.S. wind plants averaged $13 billion/year between 2008 and 2013. Domestic manufacturing content for some large, key components, such as blades and towers, ranged between 50 percent and 80 percent in 2012. Domestic content for nacelle components was significantly lower. In total, the domestic share of total wind project costs (considering turbines and balance of plant) was approximately 60 percent in 2012 (Wiser and Bolinger, 2014). Moreover, in 2013, the wind supply chain included more than 560 facilities across 43 states

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(AWEA, 2014a). Given the challenges of moving large wind turbine components over long distances, continued U.S. manufacturing and supply chain vitality is expected to be at least partially coupled to future levels of domestic demand for wind equipment. Recent fluctuations in demand and market uncertainty have forced some manufacturing facilities to furlough employees and others to cease operations altogether.

Increasing wind power is providing local economic and environmental benefits. A study of economic development impacts for wind power installations between 2000 and 2008 found that total county personal income was 0.2 percent higher and employment 0.4 percent higher in counties with installed wind power, relative to those without wind installations (Brown et al., 2012). Another study of four rural counties in west Texas found cumulative economic activity resulting from wind investments in local communities to be nearly $520,000 (2011$) per megawatt of installed capacity over the 20-year lifetime of the wind plant (Slattery et al., 2011). In 2013, more than 50,000 onsite and supply-chain jobs were supported nationally by wind investments (AWEA, 2014a). Also in 2013, wind generation was responsible for reductions of 115 megatonnes of CO_2 emissions, 157 kilotonnes of SO_2 emissions, 97 kilotonnes of NO_x emissions, and 36.5 billion gallons of water consumption (AWEA, 2014b).

Despite the recent progress, several factors challenge wind power's continued growth. Low natural gas prices have reduced wholesale power prices in recent years, while electricity demand growth has been stagnant since 2008. Wind power still grew during this period with the help of state and federal policy support. A lack of policy stability, however, could harm wind power's continued economic competitiveness and growth. Prior expirations and extensions of the federal wind production tax credit (PTC) have created a boom-bust wind cycle (**Figure 1**). These challenging electricity market conditions and the latest expiration of the federal PTC present obstacles for continued robust growth of wind.

Further challenges for wind deployment relate to transmission. Many sites with high-quality wind resources have minimal or no access to electrical transmission, which creates a bottleneck to cost-effective wind deployment. Various efforts have yielded progress on overcoming transmission barriers. For example, the Competitive

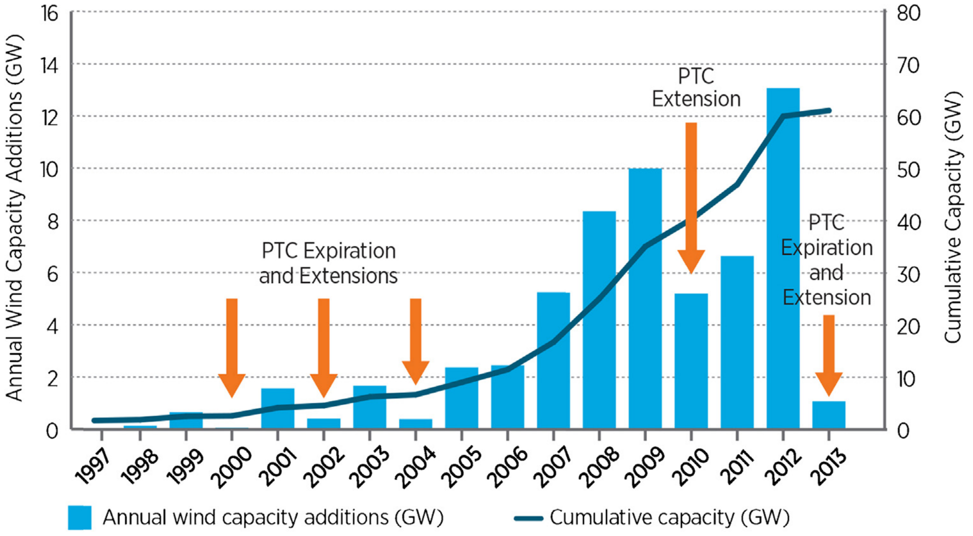

Figure 1: Historical Wind Deployment Variability and the PTC
Note: On January 1, 2014, the PTC expired again and lapsed for more than 11 months. In early December 2014, the PTC was extended again, but was valid only through year-end 2014.

Renewable Energy Zones Plan in Texas enabled transmission expansion to connect wind-rich resources in West Texas to population centers in the state's central and eastern regions (ERCOT, 2008). Such an effort could be a model for transmission expansion in other regions.

Various additional issues related to wind deployment present challenges as well. Adverse impacts of wind on wildlife and local communities must be managed through careful siting, thoughtful public engagement, and mitigation strategies. A number of government agencies, industry organizations, researchers, academics, non-governmental organizations, and collaborative groups are addressing wind-related issues, from permitting and environmental oversight to manufacturing and workforce training. Streamlining regulations is a top priority: highly variable regulatory requirements across jurisdictions and projects create uncertainties in development timelines and increase risks to successful project development.

Overcoming these challenges will be necessary for continued, sustained growth in U.S. wind development and realizing the benefits that would accompany increased wind generation. The *Wind Vision* study assesses the potential costs, benefits, and impacts associated with future wind deployment using, in part, a scenario analysis approach.

III. Defining the *Wind Vision* Study Scenario

To frame the analysis, the *Wind Vision* started with business-as-usual (BAU) conditions. Analysis was performed using the National Renewable Energy Laboratory's Regional Energy Deployment System[2] (ReEDS) capacity-expansion model and other supporting analyses. The ReEDS model relies on system-wide least-cost optimization to estimate the type and location of fossil, nuclear, renewable, and storage resource development; the transmission infrastructure expansion requirements of those installations; and the generator dispatch and fuel needed to satisfy regional demand requirements and maintain grid-system adequacy. The model considers technology, resource, and policy constraints.

Adverse impacts of wind on wildlife and local communities must be managed through careful siting, thoughtful public engagement, and mitigation strategies.

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

BAU conditions, under which wind power is only deployed where it is economically competitive and not considering societal benefits, indicate that growth in wind power will be limited through 2030, with more robust growth occurring between 2030 and 2050. Wind generation is projected to settle at about 7 percent of total electricity demand in 2016 after projects currently under construction (and qualifying for the federal PTC) are placed into service. BAU modeling projects minimal further growth to 10 percent by 2030. For the period 2015–2030, average annual new capacity additions are estimated at 3 GW/year, substantially below recent capacity additions. Negative impacts to the wind industry manufacturing sector and employment would be expected under BAU through 2030. After 2030, however, wind becomes more competitive because of

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continued cost improvements, projected increases in fossil fuel prices, and increased demand for new power generation. As a share of total U.S. electricity demand, wind power reaches 25 percent in 2050 under the *BAU Scenario*, with average annual new capacity additions from 2031 to 2050 corresponding generally to historical levels of capacity additions between 2009 and 2013.

In addition to this *BAU Scenario*, an array of sensitivities to market conditions that are unfavorable and favorable to wind were also evaluated. This analysis found that a combination of low future wind power costs and high fossil fuel prices could support wind generation levels well above the levels found under BAU conditions (**Figure 2**). The *Wind Vision Study Scenario*—where wind provides 10 percent of end-use electricity demand by 2020, 20 percent by 2030, and 35 percent by 2050—was identified based on this analysis as a credible scenario that extends recent wind deployment trends, leverages the existing domestic wind industry manufacturing base, and complements the broader literature as well as up-to-date insights into grid-integration management and transmission capacity.

The *Study Scenario* provides an analytic mechanism to evaluate the costs, benefits, and impacts of sustained growth in wind power in the United States. This scenario with aggressive but attainable wind penetration levels is compared with a *Baseline Scenario* in which wind capacity is fixed at 2013 levels (61 GW) for all future years. Comparing results from the *Study Scenario* with the *Baseline Scenario* enables an estimation of the incremental impact of all future (post-2013) wind deployment.

Sensitivity analyses within the *Study Scenario*, maintaining the same wind penetration levels, are used to assess the robustness of key results and highlight the impacts of varying wind power costs and fossil fuel prices. In the *Wind Vision* report, many of the results emphasize outcomes across the full range of sensitivities; however, this article primarily presents impacts for a single, central case. This *Central Study Scenario* applies inputs common with the *BAU Scenario* for technology cost and performance, fuel pricing, and policy treatment, but it differs from that scenario in its reliance on the prescribed *Study Scenario* growth trajectory: 10 percent wind by 2020, 20 percent by 2030, and 35 percent by 2050.

Although U.S. wind generation as of 2013 was entirely land-based, the *Wind Vision* analysis recognizes that offshore wind reached 6.5 GW globally in 2013 and that a number of U.S. offshore projects are being developed. The *Study Scenario* includes explicit allocations for land-based and offshore wind (**Figure 3**). Near-term (through 2020) offshore contributions are estimated based on U.S. projects in advanced

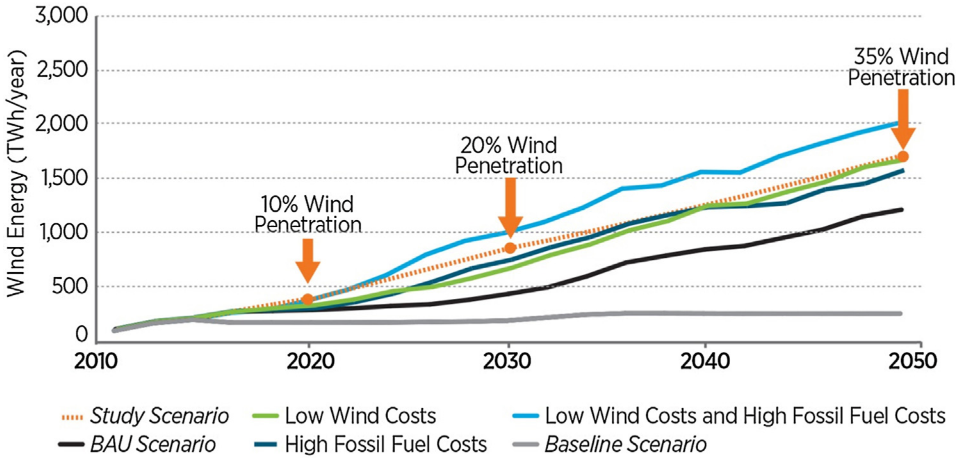
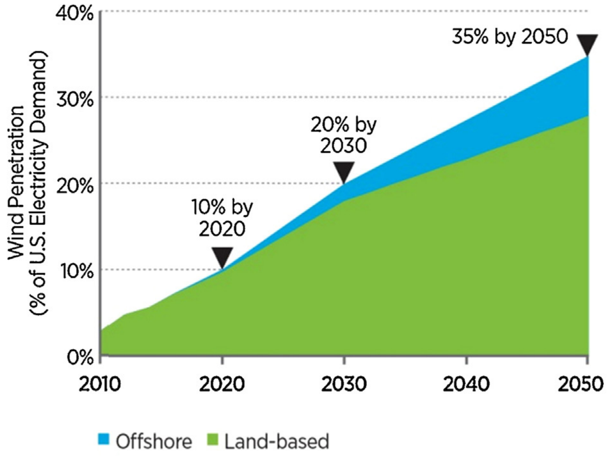


Figure 2: *Wind Vision Study Scenario* Relative to *BAU Scenario* and Sensitivities



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**

Figure 3: The *Wind Vision Study Scenario* and *Baseline Scenario*
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.

stages of development 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, whereby offshore wind provides 2 percent of U.S. electricity demand in 2030 and 7 percent in 2050. Distributed wind applications (connected physically or virtually on the customer side of the meter) are not explicitly represented but are considered as part of the broader land-based capacity associated with the *Study Scenario*.

IV. Wind-Industry and Electric-Sector Impacts of the *Study Scenario*

In the *Central Study Scenario*, total installed wind capacity increases from 61 GW at year-end 2013 to approximately 113 GW by 2020, 224 GW by 2030, and 404 GW by 2050. Of these installations, offshore wind constitutes 3 GW in 2020, 22 GW in 2030, and 86 GW in 2050. Wind power growth under the *Study Scenario* uses approximately 5 percent of the nation's available land-based wind resource and 5.5 percent of the available offshore wind resource.

The *Study Scenario* supports new wind capacity additions at levels comparable to the recent past, but it drives increased demand for new wind turbine equipment through repowering needs (**Figure 4**). Demand for wind turbines averages approximately 8 GW/year from 2014 to 2020 and 12 GW/year from 2021 to 2030, and it increases to 18 GW/year from 2031 to 2050. While aggregate demand trends upward, it is primarily concentrated in the new land-based segment in the near term. Deployment of offshore plants and repowering (the replacement of turbine equipment at the end of its useful life with new state-of-the-art turbine equipment) become more significant segments of the industry in the 2031–2050 timeframe.

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

The *Study Scenario* suggests continued geographic diversity in wind power deployment (**Figure 5**). By 2050, wind capacity

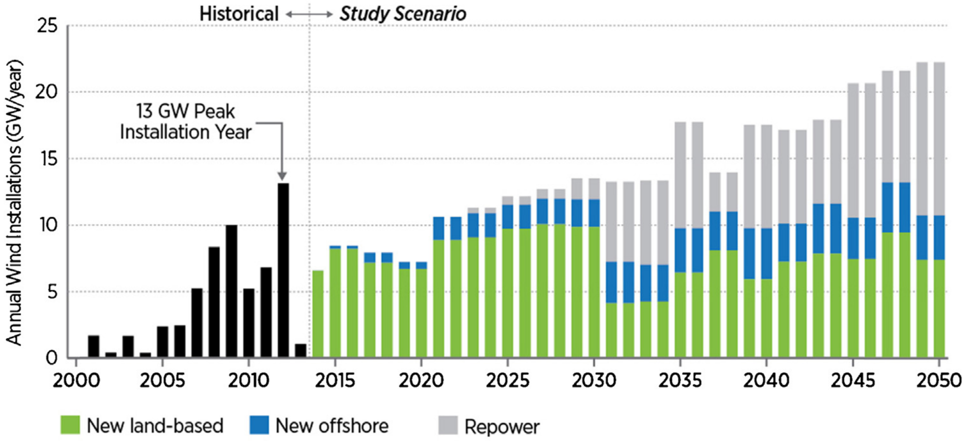


Figure 4: Historical and *Study Scenario* Annual Wind Capacity Installations
Note: New capacity installations include capacity added at a new location to increase the total cumulative installed capacity or to replace retiring capacity elsewhere. Repowered capacity reflects turbine replacements occurring after plants reach their useful lifetime. Wind installations shown here are based on model outcomes for the *Central Study Scenario* and do not represent projected demand for wind capacity. Levels of wind capacity to achieve the penetration trajectory in the *Study Scenario* will be affected by future advancements in wind turbine technology, the quality of the wind resource where projects are located, and market conditions, among other factors.

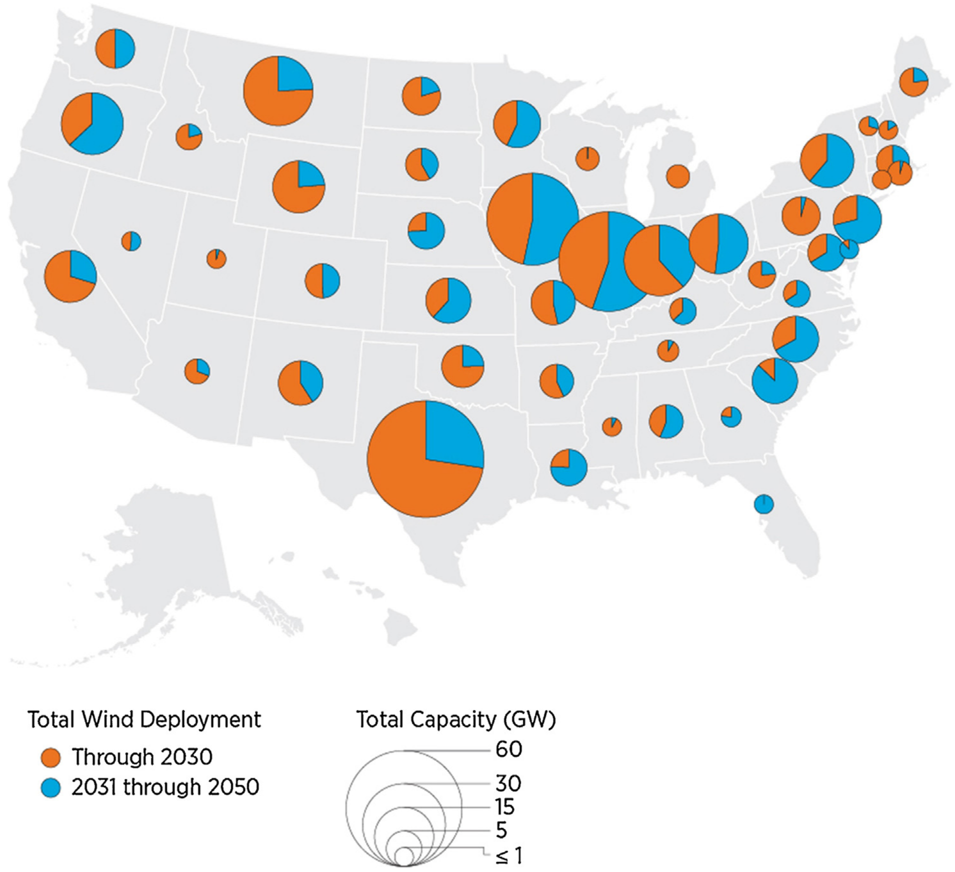


Figure 5: *Study Scenario* Distribution of Wind Capacity by State in 2030 and 2050
Note: Results presented are for the *Central Study Scenario*. Across *Study Scenario* sensitivities, deployment by state may vary depending on changes in wind technology, regional fossil fuel prices, and other factors. ReEDS model decision-making reflects a national optimization perspective. Actual distribution of wind capacity will be affected by local, regional, and other factors not fully represented here. Alaska and Hawaii already had wind deployment in 2013. However, future deployment estimates are limited to the 48 contiguous United States due to modeling limitations.

exists in all 50 states, with 40 states having more than 1 GW of installed wind capacity. Note that, although Alaska and Hawaii have significant wind deployment as of 2013, modeled future growth was restricted to the 48 contiguous states. Variations in wind resource quality, relative distances to load centers, and existing infrastructure drive regional differences in modeled wind penetration levels. Wind penetration levels exceed 40 percent across much of the West and Upper Midwest by 2050, with less substantial—but still sizeable—levels in other parts of the country. In the Southeast, wind penetration levels are lower than in other regions, but they are significantly higher than levels found in that region in 2013, particularly for coastal areas.

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

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

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

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V. Costs and Benefits of the *Study Scenario*

National average retail electricity prices for the *Baseline Scenario* and the *Study Scenario* grow (in real terms) between 2013 and 2050. Based on the assumptions of the study (for details, see DOE, 2015), through 2030, retail electricity prices in the high-wind-penetration *Study Scenario* are less than 1 percent higher than in the *Baseline Scenario*. In the long term (2050), on the other hand, retail electricity prices are expected to be 2 percent lower in the *Study Scenario*, as wind energy costs are presumed to decline while fossil energy costs increase. On an annual basis, the impacts on electricity consumers in the *Study Scenario* are estimated to include costs of $2.3 billion (0.06 ¢/kilowatt-hour [kWh]) compared to the *Baseline Scenario* in 2020, costs of $1.5 billion (0.03 ¢/kWh) in 2030, and savings of $13.7 billion (0.28 ¢/kWh) in 2050. A wider range of future costs and savings are possible as estimated by the sensitivity scenarios (Table 1): electricity costs and savings driven by future wind deployment will depend strongly on future technology and fuel price conditions.

In present-value terms, cumulative electric-sector expenditures (fuel, capital, operating, and transmission) are lower for the *Study Scenario* than for the *Baseline Scenario* under *Central* conditions[4] and many sensitivities. From 2013 to 2050, the *Central Study Scenario* results in cumulative present-value (3 percent real discount rate) savings of approximately $149 billion (−3%). Potential electricity-sector expenditures range from savings of $388 billion (−7%) to a cost increase of $254 billion (+6%), depending on future wind power cost trends and fossil fuel prices.

The *Study Scenario* reduces electric-sector lifecycle GHG emissions by 6 percent in 2020 (0.13 gigatonnes CO_2-equivalents), 16 percent in 2030 (0.38 gigatonnes CO_2-equivalents), and 23 percent in 2050 (0.51 gigatonnes CO_2-equivalents), compared to the *Baseline Scenario*. Cumulative GHG emissions are reduced by 12.3 gigatonnes CO_2-equivalent from 2013 to 2050 (14%). Based on the U.S. Interagency Working Group's Social Cost of Carbon (IWG, 2013) estimates, these reductions yield global avoided climate change damages estimated at $85–$1,230 billion, with a central estimate of $400 billion (2013–2050 discounted present value). This is equivalent to a benefit of wind energy that ranges from $7–100/MWh of wind, with a central benefit estimate of $32/MWh of wind.

The *Study Scenario* also reduces other air pollutants (e.g., $PM_{2.5}$, SO_2, and NO_x), yielding societal health and environmental benefits ranging from $52 to $272 billion (2013–2050, discounted present values) depending on the methods of quantification (Krewski et al., 2009; NRC, 2010; Lepeule et al., 2012; Siler-Evans et al., 2013). Most benefits come from reduced premature mortality due to reduced SO_2 emissions in the eastern United States. In total, the health and

Table 1: Change in Electricity Prices and Costs for the Study Scenario Relative to the Baseline Scenario.

	2020	2030	2050
Central Study Scenario Electricity Price (Change from *Baseline Scenario*)	0.06 ¢/kWh cost (+0.60%)	0.03 ¢/kWh cost (+0.30%)	0.28 ¢/kWh savings (−2.2%)
Central Study Scenario Annual Electricity Consumer Costs (Change from *Baseline Scenario*)	$2.3 billion costs	$1.5 billion costs	$13.7 billion savings
Study Scenario Sensitivity Range (% Change from *Baseline Scenario*)	+0.2% to +0.9%	−2.4% to +3.2%	−5.1% to +4.8%
Study Scenario Annual Electricity Consumer Costs Range (change from *Baseline Scenario*)	$0.8 to $3.6 billion costs	$12.3 billion savings to $14.6 billion costs	$31.5 billion savings to $26.9 billion costs

Note: Expenditures in 2013$.

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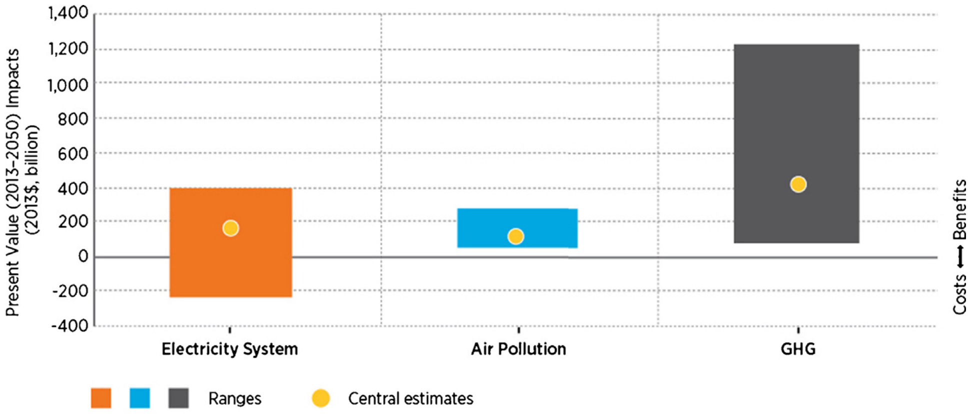

Figure 6: Cumulative (2013–2050) Present Value of Monetized Impacts of the *Study Scenario* Relative to the *Baseline Scenario*
Note: Results represent the present value of incremental costs or benefits (impacts) of the *Study Scenario* relative to the *Baseline Scenario.* Central estimates are based on *Central Study Scenario* modeling assumptions. The electricity system cost range reflects incremental expenditures (including capital, fuel, and O&M for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the *Central Study Scenario* only, with ranges derived from the methods applied and detailed in the full report.

environmental benefits are equivalent to a benefit of wind energy ranging from $4/MWh of wind to $22/MWh of wind.

The *Study Scenario* reduces national electric-sector water withdrawals (1 percent in 2020, 4 percent in 2030, and 15 percent in 2050) and water consumption (4 percent in 2020, 11 percent in 2030, and 23 percent in 2050) compared to the *Baseline Scenario*. Anticipated reductions exist in many parts of the United States, including the water-stressed arid states in the Southwest. Reduced water use would have environmental and economic benefits and would reduce competition for scarce water resources.

The value of reduced GHG and air pollution emissions in the *Study Scenario* relative to the *Baseline Scenario* exceeds the less-than-1-percent increase in electricity rates in 2020 and 2030. By 2050, the *Study Scenario* results in annual and cumulative savings across all three categories—electricity costs, GHG emissions, and air pollution emissions (Figure 6).

VI. Other Impacts of the *Study Scenario*

A variety of other possible impacts of wind deployment were considered in the analysis. In particular, the *Study Scenario* is found to reduce long-term natural gas price risk and natural gas prices, compared to the *Baseline Scenario*. The *Study Scenario* results in total electric system costs that are 20 percent less sensitive to long-term fluctuations in coal and natural gas prices. Additionally, the *Study Scenario* leads to a potential $280 billion in consumer savings due to reduced natural gas prices outside the electric sector, equivalent to a levelized consumer benefit from wind energy of $23/MWh of wind (these consumer savings, however, represent a transfer payment from natural gas resource owners and producers).

The *Study Scenario* also supports a robust domestic wind industry, with wind-related gross jobs from investments in new and operating wind plants ranging from 201,000 to 265,000 in 2030 and increasing to 526,000 to 670,000 in 2050. The number of future wind-related jobs (onsite, supply chain, and induced) will depend on the future strength of the domestic supply chain, and growth in wind-related jobs will be offset by slower growth or lost jobs in other sectors of the economy.

Under the *Study Scenario*, wind power capacity additions lead to land-based lease payments increasing from $350 million in 2020, to $650 million in 2030, and to $1,020 million in 2050. Offshore wind lease payments increase from $15 million in 2020, to $110 million in 2030, and to $440 million in 2050. Property tax payments associated with wind projects are estimated to be $900

Table 2: Top-Level Roadmap Themes and Action Areas.

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 competiveness, 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 midterm 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.

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million in 2020, $1,770 million in 2030, and $3,200 million in 2050.

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

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

VII. A Path Forward

Although the *Wind Vision Study Scenario* represents a potential future for wind growth, it is unlikely to be realized without continued technology and systems improvements. For this reason, the *Wind Vision* study includes a detailed roadmap of technical and institutional actions necessary to overcome the challenges to wind power contributing toward a cleaner, low-carbon, domestic energy economy. **Table 2** summarizes the roadmap's key themes, issues addressed, linkages to the *Study Scenario*, and action areas. These elements are detailed in the full *Wind Vision* report (DOE, 2015).

The roadmap defines specific top-level activities for all major stakeholder sectors, providing a flexible framework from which others can define specific activities at greater levels of detail. Without actions to improve wind's competitive position in the market, such as those described in the roadmap, the nation risks losing its existing wind manufacturing infrastructure and a range of public benefits as summarized earlier. The intention is that the roadmap be updated on a regular basis by the full range of key stakeholders to adjust for changing technological, market, and political conditions through 2050.

Though the roadmap includes actions intended to inform policy analysis, it is beyond the scope of the *Wind Vision* to suggest policy preferences or recommendations. Nonetheless, one core challenge of the *Study Scenario* is that current policies and market economics lack mechanisms to recognize the full value of low-carbon, low-pollution generation. The identified roadmap actions can help reduce the cost of wind energy, thereby lowering the cost of curbing future emissions and complementing any low-carbon policies that are enacted to, in part, support wind deployment.

VIII. Conclusions

One of the greatest challenges for the United States in the 21st century is providing clean, affordable, and secure energy. The *Wind Vision* demonstrates the benefits of using large-scale deployment of wind power to help meet that challenge. The *Wind Vision* analysis models a *Study Scenario* (with various sensitivities) in which 10 percent of the nation's electricity demand is met by wind power in 2020, 20 percent by 2030, and 35 percent by 2050. The near-term (2020) and mid-term (2030) incremental costs associated with large-scale wind deployment are less than 1 percent. Over the long term (through 2050), the *Study Scenario* offers net savings to the electric-power sector and electricity consumers as wind costs decline and fossil costs rise.

Increasing wind deployment also provides benefits related

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to climate change, air quality, public health, energy diversity, and water security. For example, the 12.3 gigatonnes of CO_2-equivalent avoided over 2013 to 2050 in the *Study Scenario* delivers $400 billion in savings from avoided global climate change damages. This is equivalent to a benefit of $32/MWh of U.S. wind energy produced. The value of wind's long-term economic and social benefits far exceeds the initial investment required.

While the wind industry is maturing, future actions remain critical to further advancing domestic wind energy. 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 are needed. Stakeholders and other interested parties must take the next steps in refining and implementing the roadmap actions to realize the national benefits detailed within the *Wind Vision*.■

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Endnotes:

1. The LCOEs do not include the federal wind production tax credit. Unless otherwise specified, all financial results reported are in 2013$.

2. See http://www.nrel.gov/analysis/reeds/ for more information about ReEDS.

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

4. *Central* conditions refer to the central wind technology costs and fossil fuel prices used for the primary scenarios presented here. Lower and higher technology and fuel price scenarios are also modeled and described more fully in the *Wind Vision* study.

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