Wind Power: How Much, How Soon, and At What Cost?

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Abstract

The global wind power market has been growing at a phenomenal pace, driven by favorable policies towards renewable energy and the improving economics of wind projects. On a going forward basis, utility-scale wind power offers the potential for significant reductions in the carbon footprint of the electricity sector. Specifically, the global wind resource is vast and, though accessing this potential is not costless or lacking in barriers, wind power can be developed at scale in the near to medium term at what promises to be an acceptable cost.

Introduction

The challenges of combating global climate change are enormous, and there is no single panacea. Instead, as suggested throughout this book, an assortment of technologies will need to be deployed, infrastructures reconfigured, and behaviors altered to slow and ultimately reverse rising carbon dioxide emissions.

Renewable energy has helped meet the energy needs of humans for millennia, and the world's renewable energy resources are enormous. Though truly comparable data on renewable resource potential do not exist, Table 1 shows that the world's resource potential far exceeds global primary energy supply, currently around 470 Exajoules (EJ), and that this potential has barely begun to be tapped (IPCC 2007b). In principal, at least, dramatically increased use of renewable energy could go a long way towards reducing energy-sector carbon emissions.

Table 1. Global Renewable Technical Potential and Use[1]

Energy Source	Estimated Available Energy Resource (EJ/yr)	Annual Use of Energy Resource in 2005 (EJ)
Hydro	62	25.8
Wind	600	0.95
Biomass	250	46
Geothermal	5,000	2
Solar Electricity	1,650	0.23
Ocean	7	insignificant

Source: IPCC (2007b); simplified by authors

[1] Other efforts to compile resource potential for a variety of renewable sources, with sometimes stark differences from those shown here, include de Vries et al. (2007), Hoogwijk (2004), Johansson et al. (2004), REN21 (2007), UNDP (2000), WBGU (2004), and World Energy Council (2007). Continued work is needed to develop resource potential estimates that use a common methodology and that are therefore truly comparable.

Unfortunately, however, renewable resources are often diffuse, location dependent, and variable. The diffuse and location dependent nature of the resources sometimes makes them prohibitively expensive to employ, while resource variability creates concerns about grid integration and system reliability. In part as a result of these factors, recent growth in the use of renewable electricity – though significant – is not on the scale needed to make a large dent in the climate problem. At the end of 2006, for example, aggregate worldwide renewable electricity capacity stood at 980 GW, predominantly from hydropower plants (Table 2). This is up from 943 MW in 2005, but represents a year-on-year growth of just 4%. In total, renewable electricity met 18.4% of global electric power demand in 2006. If one excludes large hydropower, however, this figure drops to just 3.4% (REN21 2008), hardly a dent given the enormity of the challenge that climate change presents (IPCC 2007a).[2] Clearly, for renewable energy to be a significant contributor to reducing global carbon emissions, a step-change in growth is required.

Table 2. Global Installed Renewable Energy Capacity

Generation Technology	Installed Capacity (end of 2006)
Large Hydropower	770 GW
Small Hydropower	73 GW
Wind	74 GW
Biomass	45 GW
Geothermal	9.5 GW
Solar Electricity	8.2 GW
Ocean	0.3 GW

Source: REN21 (2008)

The aim of this chapter is to discuss the important role that wind power *could* play in achieving carbon emissions reductions, as well as some of the barriers to that outcome. Wind power is a mature, zero-emission technology that offers an immediate option for reducing the carbon footprint of the electricity sector. In good wind resource regimes, its costs are comparable to fossil-fuel generation, adequate wind resources are available throughout the globe, and there are no insurmountable technical barriers to dramatically increased deployment of this technology. Along with other important near-term strategies, increased deployment of wind can help buy time as newer technologies are developed (e.g., low-cost solar, carbon sequestration, biofuels) or as other technologies seek greater public acceptance (e.g., nuclear power). And, because wind power represents a relatively low-cost carbon abatement option, its potential for carbon emissions reductions extends beyond the near term. Indeed, wind offers at least one important "wedge" for reducing carbon emissions (Socolow and Pacala 2006), and the analysis presented in this chapter suggests that a significant expansion of wind deployment can be achieved at what many would consider to be an acceptable cost.

[2] To achieve stabilization at 535-590 ppm CO2-equivalent, for example, the IPCC (2007a) estimates that CO2 emissions must peak from 2010-2030, and then drop to -30% to +5% of 2000 levels by 2050. A number of governments have expressed the desire to keep concentrations of CO2 well below this level, requiring even-more dramatic reductions in CO2 emissions, and some scientists have called for stabilization levels as low at 350 ppm (Hansen et al. 2008).

This chapter begins with an overview of the global wind power market, emphasizing historical growth trends, cost comparisons, and forecasts for future growth. To assess the feasibility of achieving even-higher levels of wind power penetration, the chapter then highlights an analysis of the technical and economic viability of wind energy meeting 20% of US electricity needs by 2030. Similar analyses conducted on a global basis are summarized, and the potential role of wind in meeting world-wide electricity needs is discussed. The chapter ends with a summary of what is needed to achieve these higher levels of wind power deployment. Though wind power is the exclusive focus of this chapter, many of the other renewable energy sources may also play important (and in some cases leading) roles in combating climate change; hydropower, geothermal, and solar electricity are discussed further in Chapters XX, YY, ZZ.

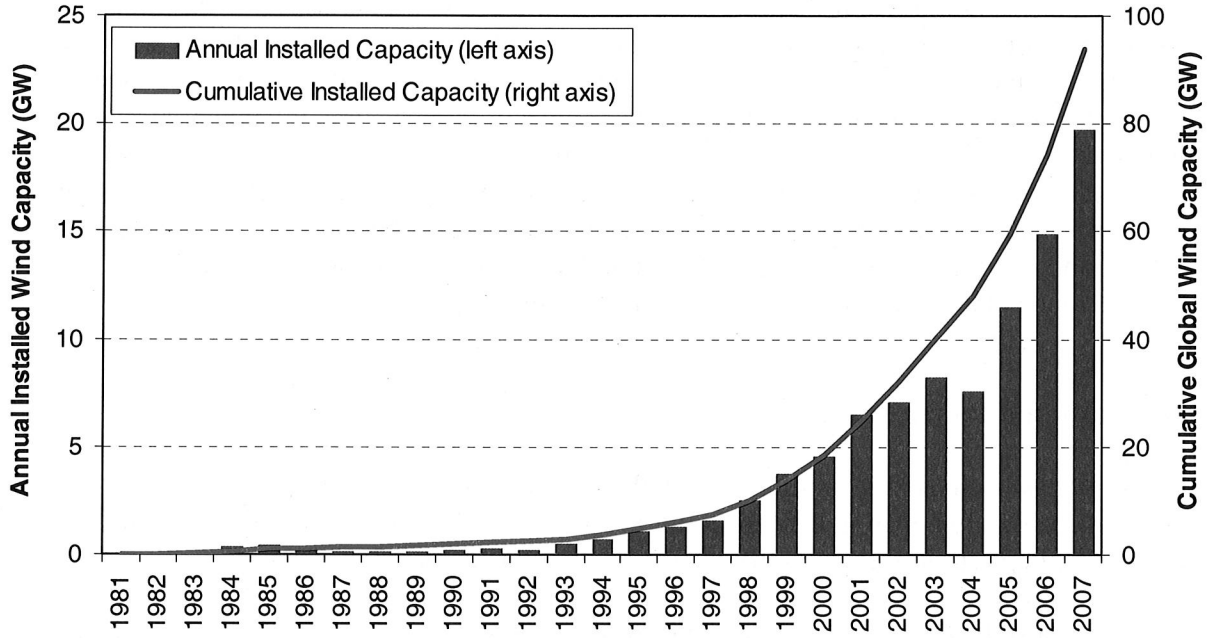
The Global Wind Power Market

Wind energy has been used for millennia, but the use of wind to generate electricity on a commercial scale only began in earnest in the 1980s. Since California's initial foray into large-scale wind deployment in the early-1980s, wind power has come a long way.

Today, a standard, land-based wind turbine stands on a tower of 60-100 meters in height, with a rotor diameter of 70-100 meters, and a power capacity of 1.5 to 3 MW. Turbines installed offshore can be even larger. Leading global wind turbine manufacturers include major industrial firms such as Vestas, General Electric, Gamesa, Enercon, Suzlon, and Siemens (BTM 2008). Increasingly, the developers and owners of wind projects are major electricity utilities and investment firms.

Global wind power capacity is growing at a rapid pace and, as a result, wind power has quickly become part of the mainstream electricity industry. In 2007, roughly 20 GW of new wind capacity was added globally, yielding a cumulative total of 94 GW (Figure 1). Since 2000, cumulative wind capacity has grown at an average annual pace of 27%. The vast majority of this capacity has been located on land; offshore wind capacity surpassed 1 GW at the end of 2007, with accelerated growth expected in the future, especially in Europe (BTM 2008, GWEC 2008).

Figure 1. Growth in Global Wind Capacity



Source: Earth Policy Institute, BTM Consult, American Wind Energy Association

Although European countries such as Germany, Denmark and Spain have led the charge over most of the past decade, the US became the fastest-growing wind power market in 2005, followed by European stalwarts Germany and Spain, as well as the up-and-coming Asian markets in China and India (Table 3). With major development now occurring on several continents, wind power is becoming a truly global electric generation resource.

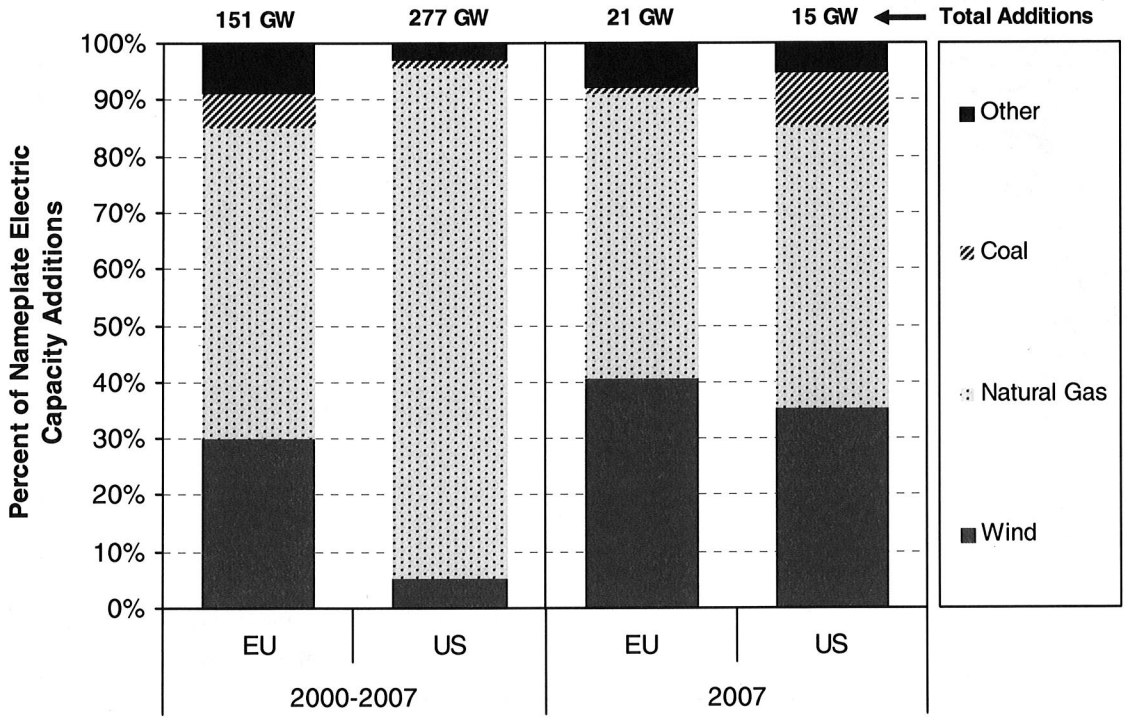
Table 3. International Rankings of Wind Power Capacity

Incremental Capacity (2007, MW)		Cumulative Capacity (end of 2007, MW)	
United States	5,329	Germany	22,277
China	3,287	United States	16,904
Spain	3,100	Spain	14,714
Germany	1,667	India	7,845
India	1,617	China	5,875
France	888	Denmark	3,088
Italy	603	Italy	2,721
Portugal	434	France	2,471
United Kingdom	427	United Kingdom	2,394
Canada	386	Portugal	2,150
Rest of World	*2,138*	*Rest of World*	*13,591*
TOTAL	**19,876**	**TOTAL**	**94,030**

Source: Wiser and Bolinger (2008)

In both Europe and the US, wind now represents a major new source of electric capacity additions. From 2000 through 2007, wind was the second-largest new resource added in the US (5% of all capacity additions) and EU (30% of all capacity additions) in terms of nameplate capacity, behind natural gas, but ahead of coal (Figure 2). In 2007, 35% of all capacity additions in the US and 40% of all additions in EU came from wind power (Wiser and Bolinger 2008, EWEA 2008).

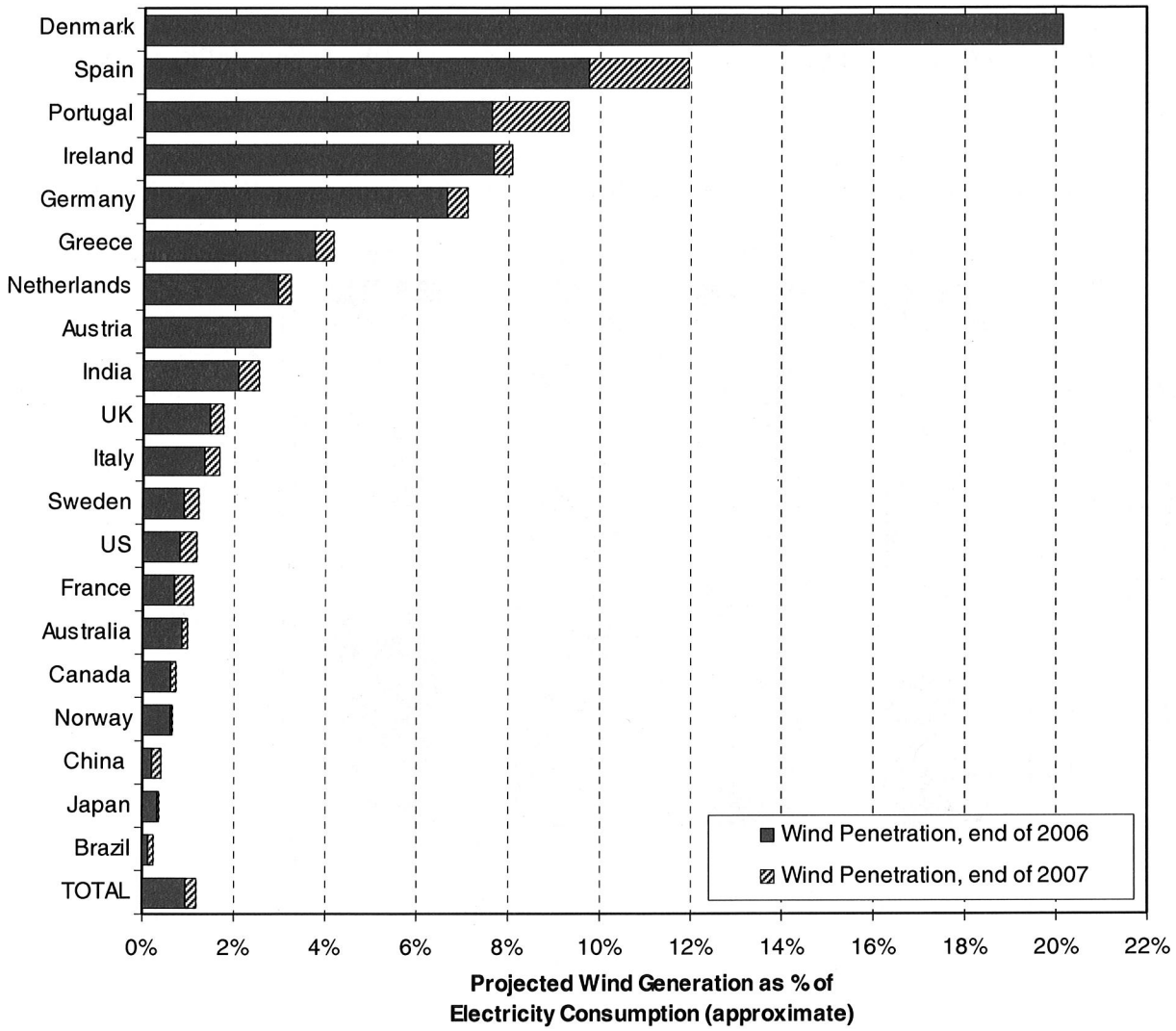
Figure 2. Relative Contribution of Generation Types to Capacity Additions in the US and EU



Source: Wiser and Bolinger (2008), EWEA (2008)

As a result of this expansion, some countries are already successfully utilizing wind as a significant contributor to overall electricity supply. Denmark, for example, generates roughly 20% of its electricity from wind, while Spain is at 12%, Portugal at 9%, Ireland at 8%, and Germany at 7% (Figure 3). On a global basis, however, wind is still an emerging player, serving 1.2% of total worldwide electricity needs (Wiser and Bolinger 2008).

Figure 3. Approximate Wind Power Penetration in the Twenty Countries with the Greatest Installed Wind Capacity



Source: Wiser and Bolinger (2008)

Though the wind capacity installed by the end of 2007 is able to contribute just 1.2% of US electricity supply, the US is one of the most dynamic markets for wind. The US has led the world in wind capacity additions for three years running (2005-2007). The 5.3 GW of wind installed in 2007 represented 27% of the worldwide wind market in that year, and was more than double the previous US installation record set in 2006. Cumulatively, at the end of 2007, nearly 17 GW of wind capacity was installed in the US. And, with at least 225 GW of in-development wind projects in transmission interconnection queues at the end of 2007, the US wind market is poised for continued strong growth in the years ahead (Wiser and Bolinger 2008).

Driving the growth both in the US and globally are a number of factors, including promotional policies (Haas et al. 2008, Lewis and Wiser 2006, Meyer 2007). In the major European markets, including Germany and Spain, aggressive feed-in tariff programs have been predominant,

offering wind power owners standardized and known payment streams (Mendonca 2007). In other markets in Europe, the US, and elsewhere, renewables portfolio standards (RPS) have come into vogue, requiring electricity suppliers to meet a specified and growing percentage of their load with renewable electricity (van der Linden et al. 2005). And, in many countries, a mixed set of policies has been used to good effect, including RPS programs and tax incentives in the US; RPS, feed-in tariffs, and tax incentives in India; and RPS, feed-in tariffs, and auctions in China. In many countries, the current reality and/or future prospect of carbon regulations has also helped motivate wind development.

Though promotional policies differ, and healthy debate exists over the relative merits of different approaches, a key finding is that policy continuity and market stability are of utmost importance. The US market, for example, has been hampered by the boom-and-bust cycle to wind project development caused by short-term extensions of that country's production tax credit (PTC) for wind (Wiser et al. 2007). [3] More generally, experience also shows that promotional policies must generally be backed by other, enabling policies, such as proactive transmission planning for wind, and siting and permitting procedures that allow development to proceed without undue impediments.

Of equal importance to the aforementioned policy drivers has been the improved underlying economics of wind power relative to fossil fuels, which is – in part – dependent on wind project performance and installed costs. In the US, wind project performance has improved with time. In 2007, for example, wind projects in the US produced power with an average capacity factor of just over 31% in aggregate. Those projects installed prior to 1998, however, maintained an average 2007 capacity factor of just 22%, while those projects installed from 2004 through 2006 averaged 34%, a significant improvement in project performance over time (left-most graphic in Figure 4). These performance improvements may be attributable to several factors, including improved turbine design, larger turbines on taller towers, and improved siting and operations.

Trends in the installed cost of wind projects are more mixed. Specifically, the average installed cost for wind projects in the US has increased significantly since the early 2000s, from $1,300/kW in 2001 to roughly $1,700/kW in 2007 (right-most graphic in Figure 4), and to more than $2,000/kW in 2008 (real 2007$).[4] These cost pressures are not, however, unique to wind; the installed cost of other generating technologies has increased by a similar magnitude (Chupka and Basheda 2007). Moreover, even at more than $2,000/kW in 2008, installed costs remain well below the $4,000/kW average seen in the early 1980s.

[3] Since 1994, the PTC has offered new wind projects in the United States a 10-year, inflation-adjusted tax credit that stood at $20/MWh in 2007. The PTC has often been extended for relatively short periods of time, however, imposing significant uncertainty to the market.

[4] Increases in the installed cost of wind projects since the early 2000s are due to numerous factors, including the weakening of the US dollar, increased materials and energy input prices, and an overall demand for wind turbines that exceeds available supply.

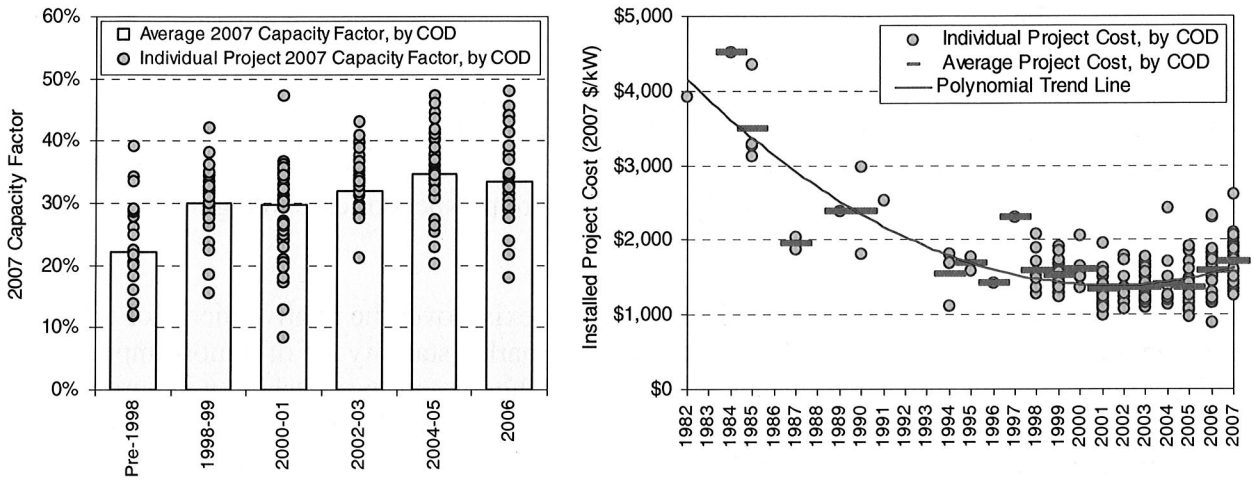


Figure 4. Trends in the Performance and Installed Cost of Wind Projects in the US, By Date of Commercial Operation (COD)

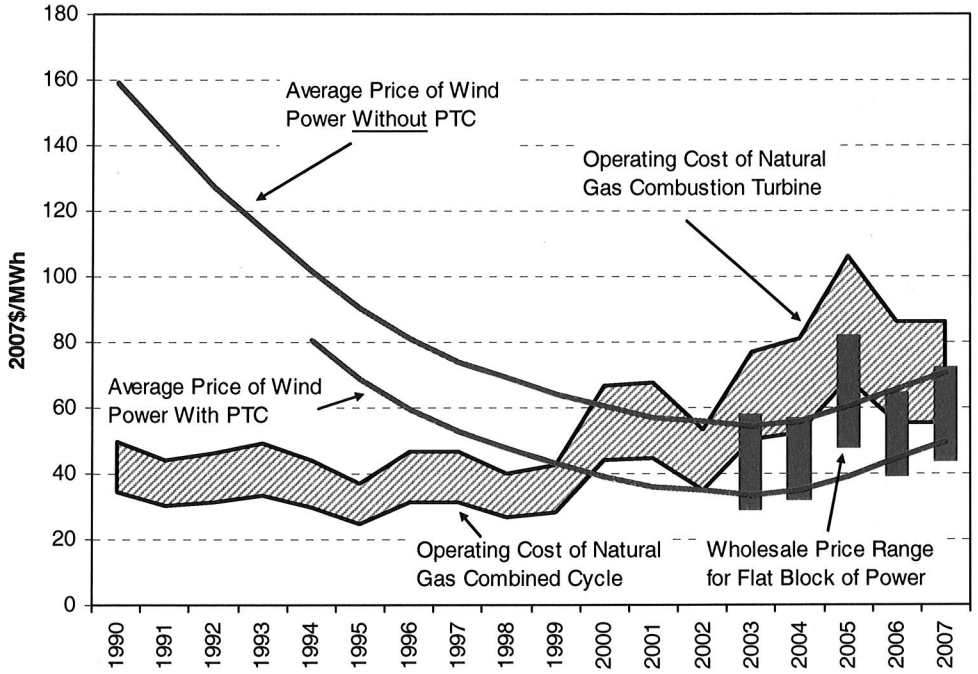
Source: Wiser and Bolinger (2008)

Figure 5 presents data on the resulting historical average price of wind power in the US, from 1990 to the present, both with and without the federal PTC. The figure also provides data on the annual fuel and variable operating cost of natural gas plants over this period, conservatively assuming that wind operates to conserve fuel and variable O&M, but that it does little to offset the need for new dispatchable power plants to maintain electricity reliability.[5] Finally, the figure provides data on the price of a flat block of power across the numerous wholesale market trading hubs in the country from 2003 through 2007; these data are lower than the average cost of operating natural gas plants because natural gas is not always the marginal resource.

Though clearly a simplified approach to comparing the economics of different energy sources, Figure 5 nonetheless shows that, since 2000, wind power with the PTC has often been economically competitive with other sources of electricity in the US. Even without the PTC, the cost of wind has not been far out-of-line with fossil-fueled generation. Moreover, though a confluence of factors has put upward pressure on wind power prices since the early 2000s, those cost pressures have affected other generation technologies as well. As a result, the relative economic position of wind has not changed dramatically over this period.

[5] In fact, a large number of studies have shown that wind does have some "capacity value", though the level of that value depends on many factors.

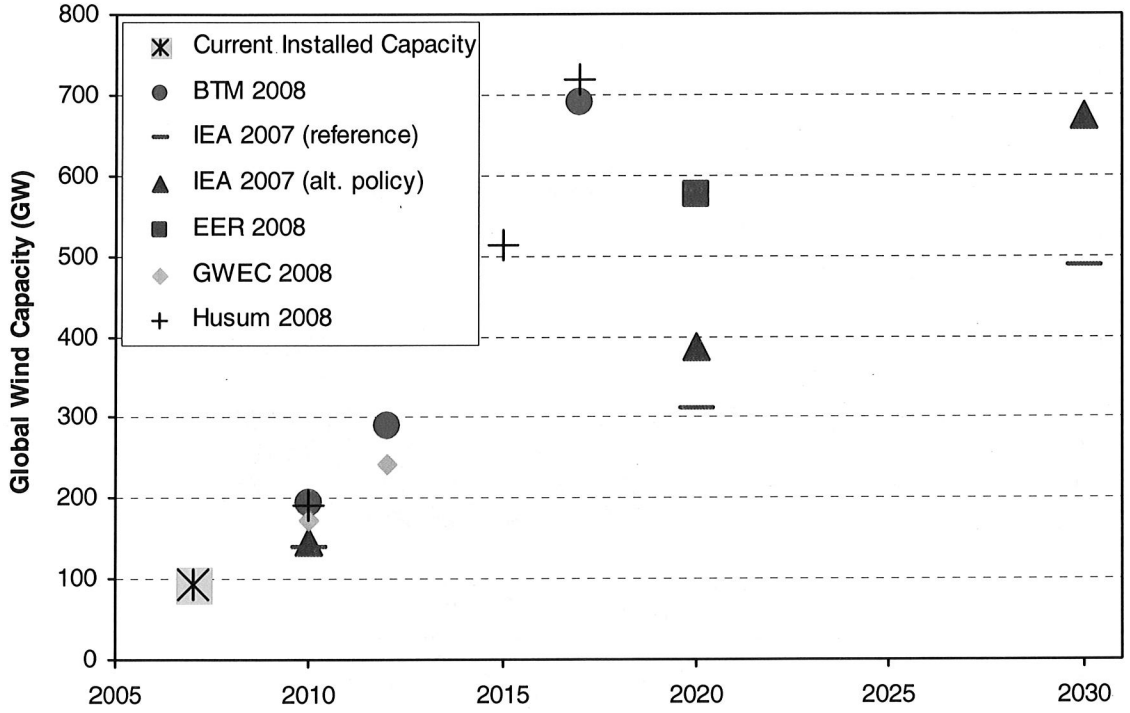
Figure 5. Comparative Economics of Wind, Natural Gas, and Wholesale Electricity Prices in the United States



Source: Prepared by Berkeley Lab based, in part, on data from EIA, NREL, and Wiser and Bolinger (2008)

Given all of these trends, wind capacity additions are likely to continue at a rapid clip, both in the US and globally. Several studies have tried to predict future global wind capacity under what might be considered business-as-usual (BAU) conditions, where existing policies are maintained but not dramatically expanded. Figure 6 presents the results of several of these studies. Though a considerable range exists, reflecting the inherent uncertainties in such predictions, it appears that 300-700 GW of wind might be expected on a global basis in the 2015 to 2030 timeframe in a BAU scenario. To put this in context, 300 GW of wind in 2015 represents more than 3% of total expected worldwide electricity supply for that year, while 700 GW by 2030 represents roughly 6% of expected supply.

Figure 6. Projections for Global Wind Capacity Growth



Source: Compiled by Berkeley Lab from the sources cited in the figure

Simply assuming that wind offsets the use of new natural gas and coal power plants in equal proportions, global wind power capacity installed at the end of 2007 was already saving roughly 34 million metric tons of carbon equivalent (MMTCE) annually. Installed capacity of 300-700 GW would raise this figure to 130-300 MMTCE/yr. Though meaningful, even this growth is modest relative to what would be needed in a deep carbon-reduction scenario (IPCC 2007a), and relative to wind's resource potential. The chapter therefore now turns to an analysis of the feasibility of achieving much higher levels of wind penetration. To provide a detailed example of such analysis, the next section focuses on the feasibility of achieving 20% wind power penetration in the US. A later section summarizes similar studies conducted on a global basis.

20% Wind Electricity by 2030

In 2008, the US Department of Energy, in collaboration with its national laboratories, the wind industry, and others, completed a major analysis of the technical and economic feasibility of wind power meeting 20% of the nation's electricity supply needs by 2030 (US DOE 2008). As discussed below, that study finds that there are no insurmountable technical barriers to achieving 20% wind penetration by 2030, and that the economic costs of doing so are likely to be modest.

The key questions addressed by this analysis included:

- Is it technically feasible to achieve 20% wind by 2030?
- Does the nation have sufficient wind resources and land area?

- What are the technology and manufacturing requirements, and are they achievable?
- Can the electric network accommodate 20% wind, and how?
- What are the likely costs and benefits of achieving 20% wind penetration?

Previous studies that have estimated the potential and costs for rapid wind energy deployment in the US have shown divergent results.[6] These results are the product of differing input assumptions and differing treatment of wind power in capacity expansion models. Modeling wind presents a unique challenge (Neuhoff et al. 2008). As a variable and non-dispatchable generation resource, wind's distinctive characteristics require changes to modeling algorithms. The nation's most robust wind resources are often located at a distance from load centers, so how new transmission is modeled is of critical importance. And because wind resources are not uniform across the nation, an appropriate modeling tool must incorporate geographic detail that can capture the nature of the underlying wind resource. Many previous efforts to evaluate wind's potential have largely ignored these details, or have instead relied on crude approximations or supply constraints that intend to loosely account for wind's unique characteristics. Though these approaches are often taken in the name of simplicity, their application can impose poorly documented and potentially unrealistic constraints and costs on wind generation that other generation sources do not face.

Though no modeling tool is perfect, the analytic backbone of the US DOE report was the Wind Energy Deployment Systems (WinDS) model.[7] WinDS is a capacity expansion model of the US electricity system. It uses a detailed geographic information system (GIS) representation of the nation's wind resources and their proximity to existing transmission infrastructure and load centers. By dividing the country into 358 distinct regions, the model uniquely represents the geographic variation of wind resources, infrastructures, and loads. WinDS also models seasonal and diurnal wind resource variations that, combined with statistical algorithms, address the variable nature of wind energy and that allow the model to incorporate the costs of integrating wind power into electric grids. In sum, WinDS provided a means of estimating the location of wind installations, the transmission infrastructure expansion requirements of those installations, and the composition of generation technologies needed to maintain reserve capacity requirements while meeting projected electricity demand.

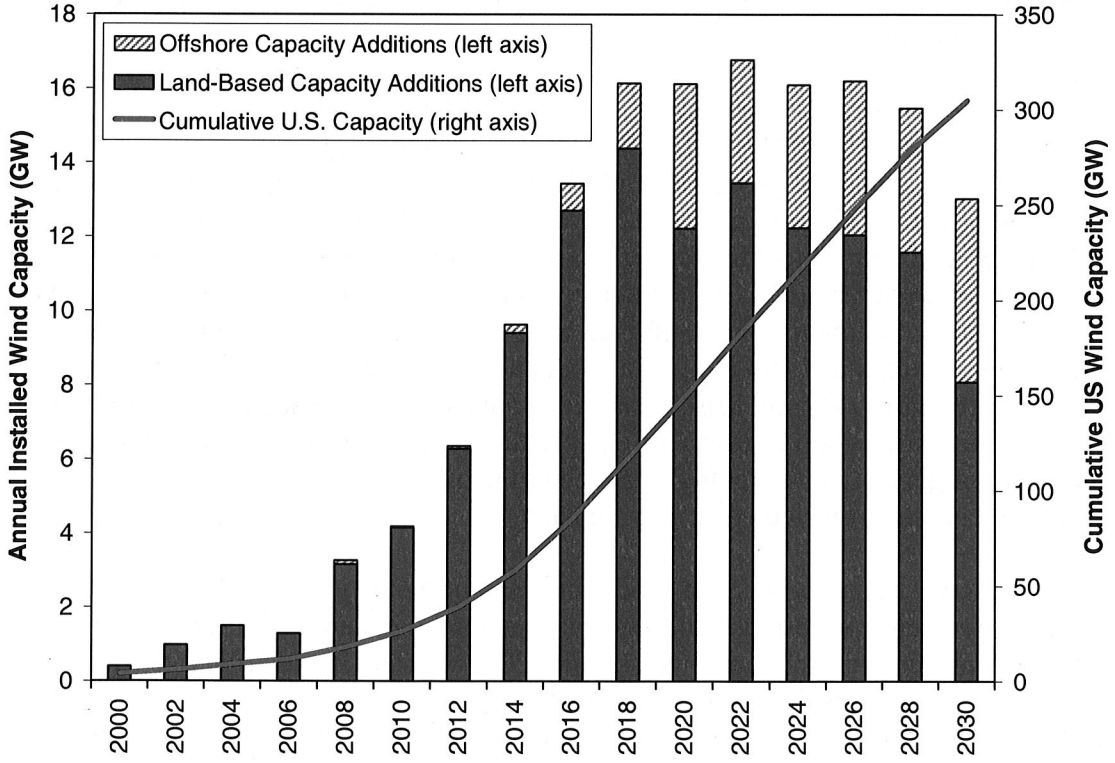
To isolate the impacts, costs, and benefits of producing 20% of the nation's electricity from wind by 2030, two scenarios were contrasted. In one scenario, annual wind energy capacity and generation growth is prescribed such that wind supplies 20% of total US electricity generation by 2030 (20% Wind scenario). The other scenario assumes no additional wind capacity after 2006 (No New Wind scenario). In both scenarios, conventional generation technologies compete for the nation's residual supply needs. To uniquely identify the costs and impacts of increased wind deployment, the modeling assumed no new policy incentives (e.g., carbon mitigation policies) and that the PTC was not available after 2008. Underlying the model were a large number of assumptions about the future cost and performance of electric generation technologies. Also, to efficiently accommodate the unique characteristics of wind, the analysis assumed that the electricity grid is operated within large, regional markets. New transmission lines are "built" by

[6] For some examples, see: Cryts et al. (2007), EIA (2008b), Hoogwijk et al. (2007), Key (2007), Kutscher (2007), Kyle et el. (2007), and Short et al. (2004).
[7] See: http://www.nrel.gov/analysis/winds/

WinDS as needed at costs that vary regionally. These latter assumptions for grid operations and transmission expansion, while not infeasible, would require the removal of significant institutional barriers to market integration and new transmission investment. For a complete account of the many assumptions behind the model, the reader is referred to the final report of the project (US DOE 2008).

Not surprisingly, the study finds that reaching 20% wind would require a dramatic increase in wind capacity. In particular, based on assumed improvements in wind project performance over time, and an assumption that transmission to access the nation's lowest-cost wind resources can be built at will (if cost-effective), 305 GW of wind capacity would be needed by 2030 (Figure 7).[8] WinDS analysis projects that more than 50 GW of this capacity would be installed offshore. From 2018 to 2030, roughly 16 GW of wind would need to be installed annually, compared to the 5.3 GW added in 2007.

Figure 7. Annual and Cumulative US Wind Capacity Installations in 20% Wind Scenario



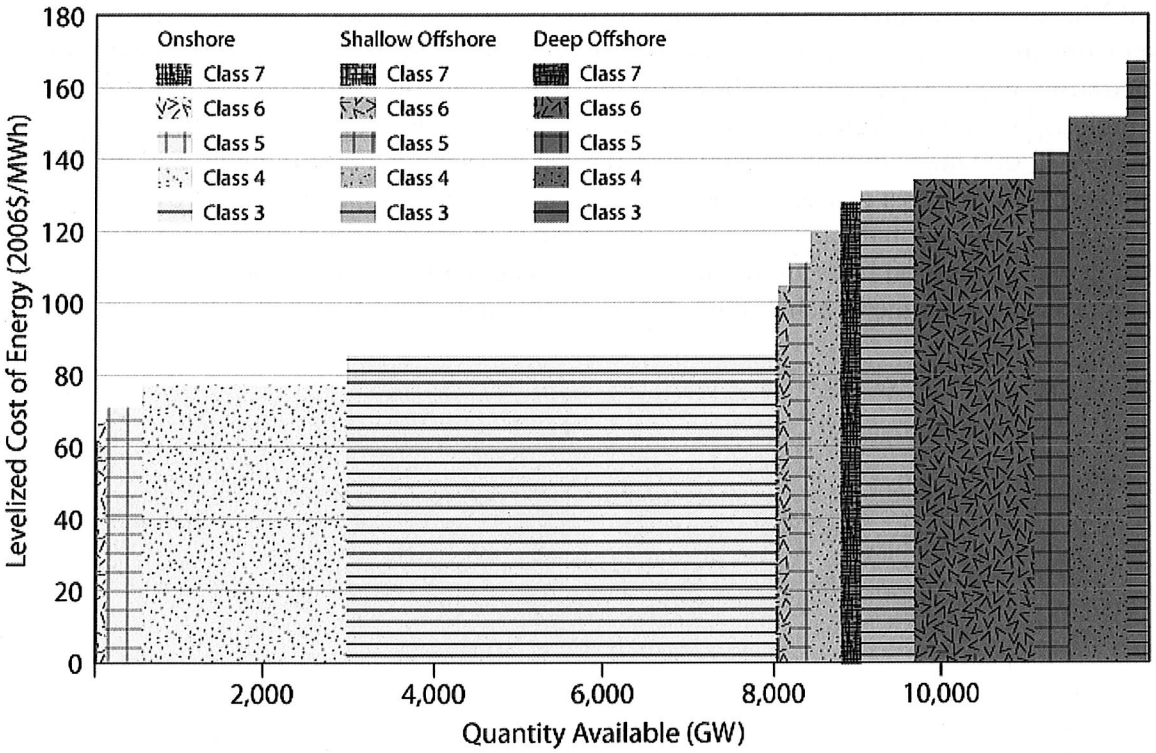
Source: Derived from US DOE (2008)

Though surely a daunting challenge, the analysis finds that the US has vast wind resources, far exceeding what is needed to achieve 20%. Considering busbar economics alone, for example, and ignoring transmission and integration costs, Figure 8 provides a supply curve for wind using

[8] If transmission could not be so-readily constructed, or if state policies shifted development towards less-cost-effective locations, then the aggregate amount of wind capacity needed to achieve 20% wind would increase, as would the incremental cost of achieving that target.

cost and performance assumptions from 2007, segmented by wind resource class and by onshore, shallow offshore, and deep offshore wind potential. Even assuming that the PTC is not available, the study find that roughly 8,000 GW of wind is potentially available at busbar generation costs of less than $85/MWh. This far exceeds the 305 GW of wind required in the 20% Wind scenario. Moreover, though not shown in the figure, even if the cost to connect to the existing transmission system or to connect to *nearby* load centers is considered, over 600 GW of wind generation potential still remains available at a cost of less than $100/MWh.[9]

Figure 8. The Supply Curve for Wind in the United States with Today's Technology



Note: This figure presents the busbar economics of wind, as a function of wind resource class, excluding the PTC as well as transmission and integration costs

Source: Derived from US DOE (2008)

The analysis also shows that there are no fundamental physical limitations to raw material supplies (e.g. sand, cement, iron ore), though the potential for shortages of processed materials like fiberglass or steel does exist and may have to be overcome. This level of growth would also require a substantial labor force. A key challenge would be to maintain downward cost pressure on installed wind project costs while the industry rapidly expands.

The study further concludes that, although sufficient land area exists, siting challenges will be significant. Figure 9 illustrates the potential location of the 305 GW of wind needed to achieve

[9] This 600 GW figure is extremely rough because it assumes that 10% of all existing transmission capacity is available for wind delivery, and completely ignores the very-real possibility of new, longer-distance transmission.

20%, based on the economic optimization routine used by WinDS.[10] As shown, WinDS adds wind capacity in almost every state; development in the Southeast is limited due to limited on-shore wind resource potential.[11] Siting this quantity of wind capacity will pose a significant challenge, and the land area requirements are not insubstantial. Assuming that the projected land-based wind turbines are all located in one wind plant, for example, that plant would cover a square roughly 225 km (140 miles) on a side, or roughly 0.5% of total US land area. Only 2-5% of this area would be occupied by turbine towers, roads, etc., with the balance available for other uses such as farming or ranching. Nonetheless, concerns about wildlife impacts, aesthetics, and other factors will surely need to be addressed to achieve this level of capacity additions.

Because the best wind resources tend to be long distances from population centers, expansion of the nation's transmission infrastructure is an essential precondition for achieving high levels of wind penetration. Figure 9 presents one broadly suggestive scenario for the wind energy transfer between regions, based on WinDS output. The 20% Wind scenario projects the addition of approximately 12,000 miles of new transmission lines at a discounted cost of about $20 billion. Although the $20 billion cost estimate is not prohibitive from the perspective of the overall electric sector, the institutional barriers to planning, siting, and recovering the cost of this quantity of new transmission lines are not insubstantial, and transmission expansion may pose the most significant challenge to achieving high levels of wind generation.

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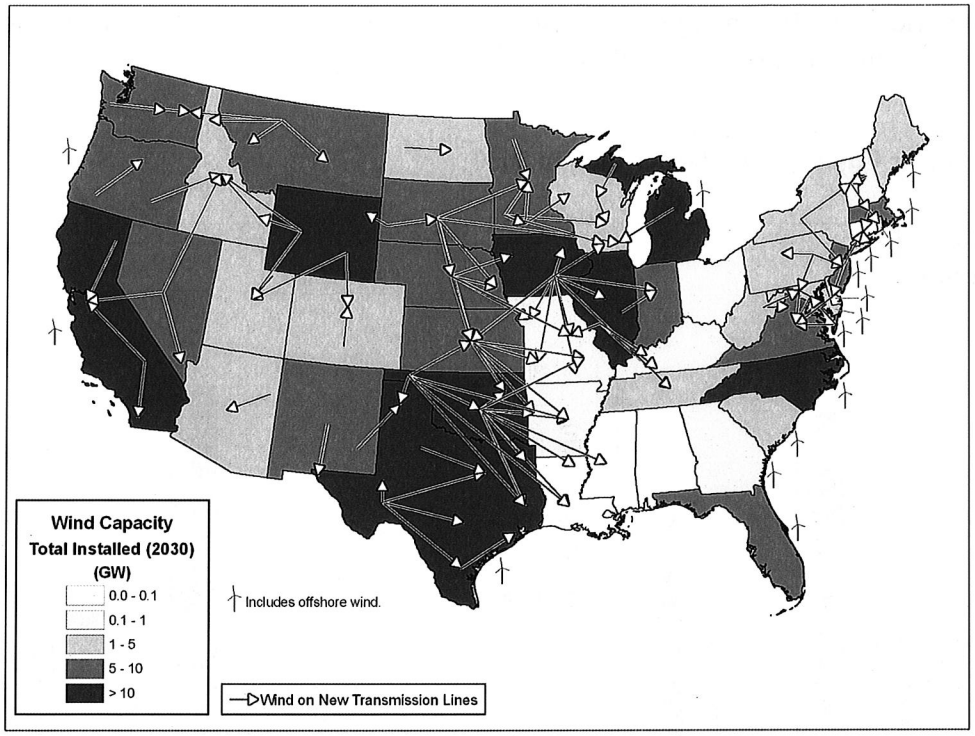
[10] The wind capacity levels projected by WinDS in each state depend on a variety of assumptions. In reality, the distribution of the 305 GW across states would differ from WinDS projections, and would depend, in part, on state policies used to promote or restrict wind energy.

[11] Alaska and Hawaii were not included in the study, but each state possesses ample wind resources and is expected to install wind capacity in the future.

Figure 9. Installed Wind Capacity by State in 2030, and New Transmission Needs



Source: Derived from US DOE (2008)

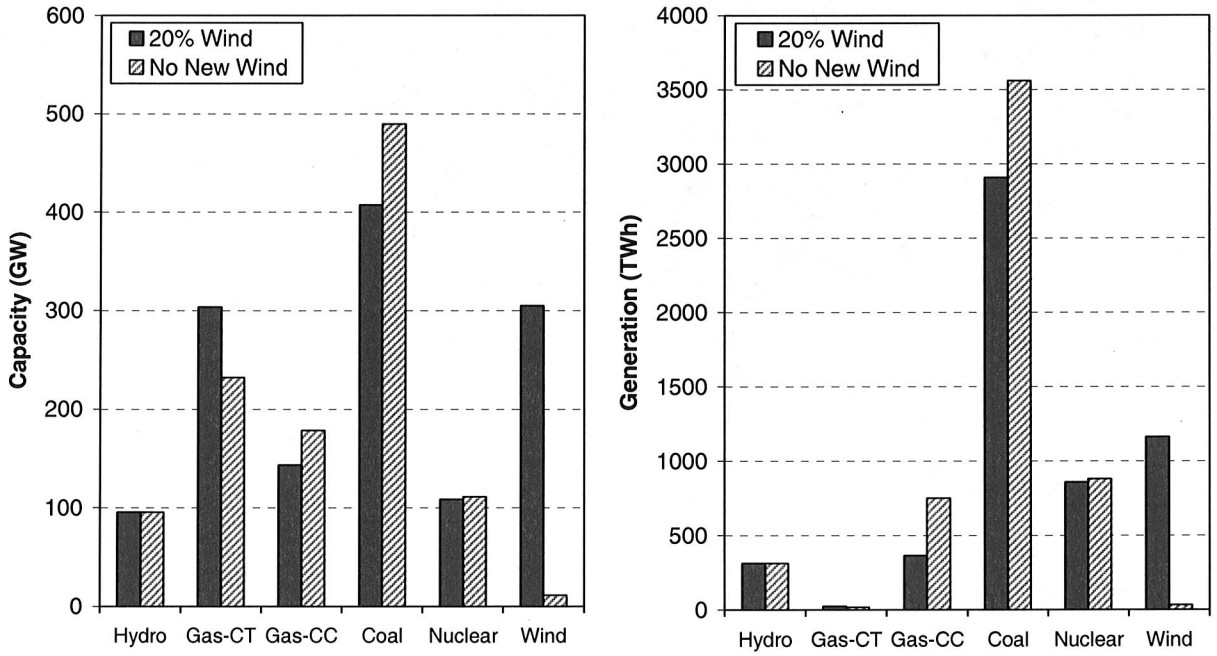
Importantly, the study also concludes that the integration of 20% wind into US electricity markets is both technically and economically feasible. In contrast to many other sources of electricity, wind power is inherently variable and non-controllable. In addition, though forecasting techniques are improving, there are limits to the level of those improvements. Despite these characteristics, a growing number of studies indicate that high levels of wind penetration can be accommodated as part of interconnected power systems.[12] Though accommodating wind requires modifications to power systems planning and operations, the costs imposed by these changes are generally found to be below $10/MWh for wind penetrations of up to 20%. Spatial diversity in wind plants, wind output forecasting, control area coordination, liquid real-time markets, and quick-ramping fossil assets can all help alleviate the inherent variability in wind generation.

The WinDS model considers the cost of integrating wind into electricity systems, as well as the cost of maintaining overall system capacity and reliability. One key output of the WinDS modeling is that the wind generation in the 20% Wind scenario offsets both coal and combined-cycle natural gas (Gas-CC) usage (see right-most graphic in Figure 10), but also leads to a significant increase in quick-ramping gas combustion-turbine capacity (Gas-CT) to maintain

[12] For summary articles on this topic, see Gross et al. (2007) and Smith et al. (2007).

system reliability (see left-most graphic in Figure 10).[13] The US DOE study concludes that additional storage is not strictly essential to achieving 20% wind penetration. Subsequent analysis confirms this result, but also finds that the economical use of storage could reduce the costs of maintaining grid reliability in high-wind penetration scenarios by, in part, reducing the need for gas combustion-turbine capacity (Sullivan et al. 2008).

Figure 10. Electric Sector Capacity and Generation in 2030



Source: US DOE (2008)

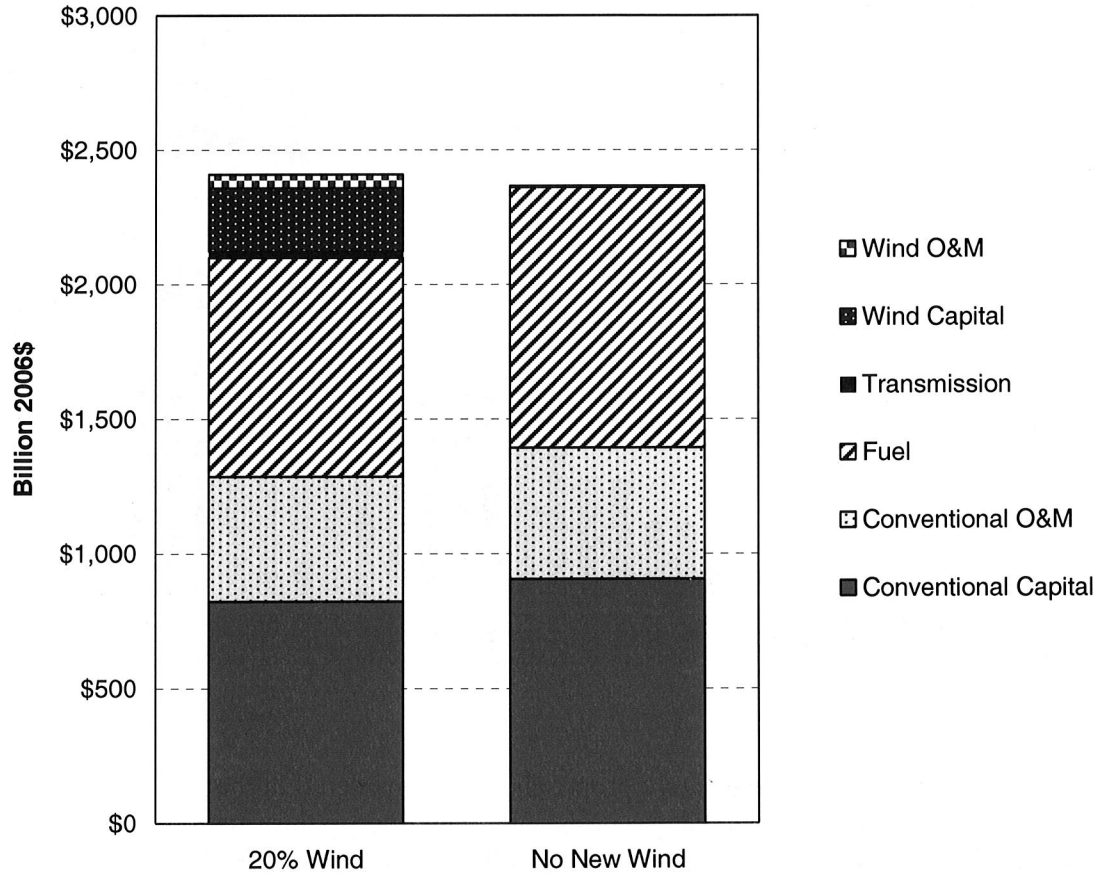
At the heart of the analysis was an assessment of the economic feasibility of achieving 20% wind, and here the news is positive: if the significant institutional barriers can be overcome, the overall incremental costs of achieving 20% wind energy are projected to be relatively modest. Figure 11 shows the total estimated electric-sector costs for both the 20% Wind and the No New Wind scenarios, considering capital costs, fuel costs, operations and maintenance costs, and transmission costs (embedded in these categories are also resource adequacy and integration costs). The 20% Wind scenario requires a larger capital investment, but that investment is offset by reduced fuel costs. In aggregate, the 20% Wind scenario imposes an estimated net discounted incremental cost of over $40 billion.[14] This implies an average incremental cost of wind (compared to the fossil generation deployed in the No New Wind scenario) of $9/MWh, an average increase in retail electricity rates of $0.6/MWh, and a bill impact for an average household of roughly $0.50 per month. Subsequent technical analysis has explored the sensitivity of this cost to differing input parameters, and has found the cost estimate be relatively robust

[13] Though, as shown in the right-most graphic in Figure 10, these gas combustion-turbine plants operate very infrequently.

[14] WinDS is used to estimate generation and transmission capital expenditures as well as fuel and O&M costs through 2030, while extrapolations of fuel usage and O&M requirements are applied from 2030 to 2050. A 7% real discount rate is used to estimate present value figures.

(Blair et al. 2008). In particular, if conservative assumptions are used, the estimated incremental cost of achieving 20% wind can, in the more extreme cases, more than double while, if more optimistic assumptions are used, aggregate electric-sector *savings* are sometimes predicted.

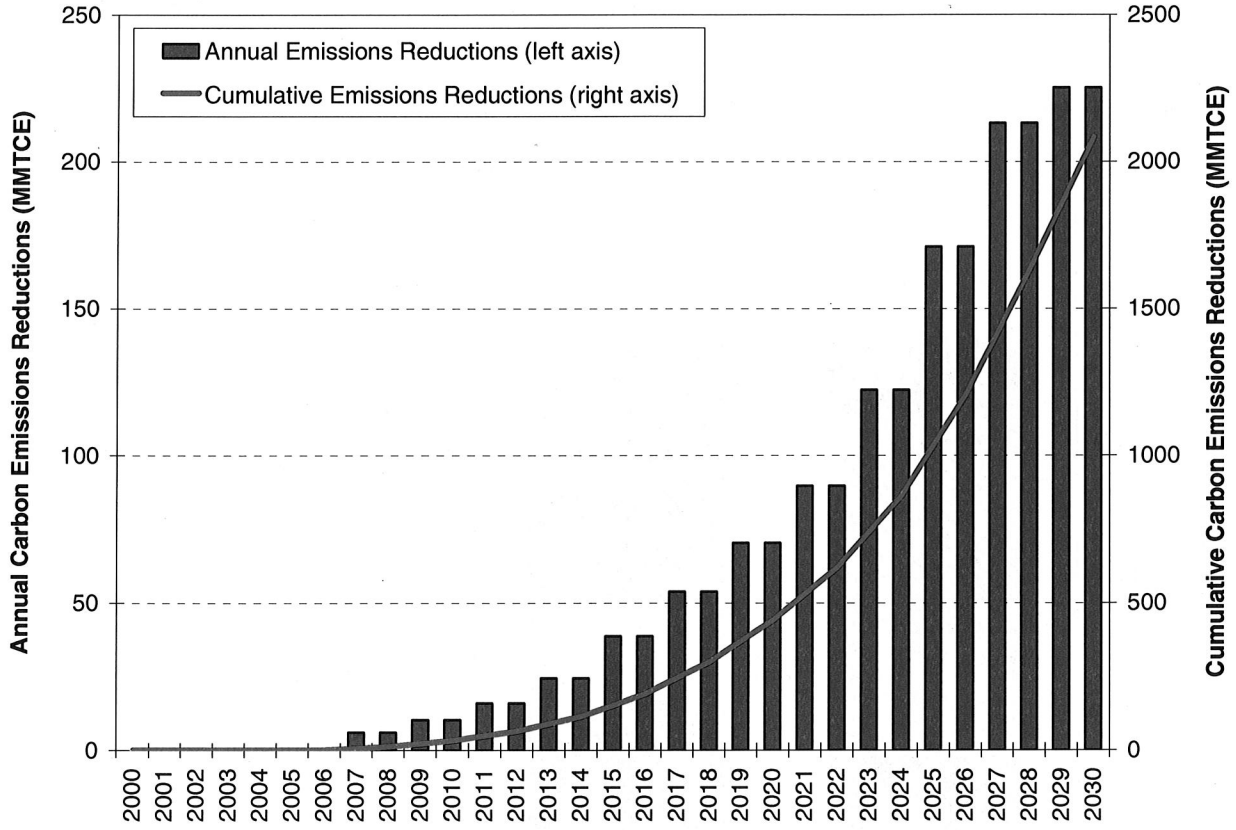
Figure 11. Total Electricity-Sector Direct Costs (discounted at 7%/yr)



Source: US DOE (2008)

Of course, these direct costs are offset by a number of *possible* benefits, including lower fossil-fuel prices, environmental improvement, reduced water consumption, rural economic development, and employment opportunities in the renewable energy sector. Perhaps most importantly, achieving 20% wind would reduce the carbon footprint of the US electricity sector. WinDS modeling shows a displacement of coal and natural-gas generation, yielding an annual reduction of 225 MMTCE by 2030, equivalent to roughly 20% of expected electricity-sector carbon emissions in 2030 in the No New Wind reference case (Figure 12).

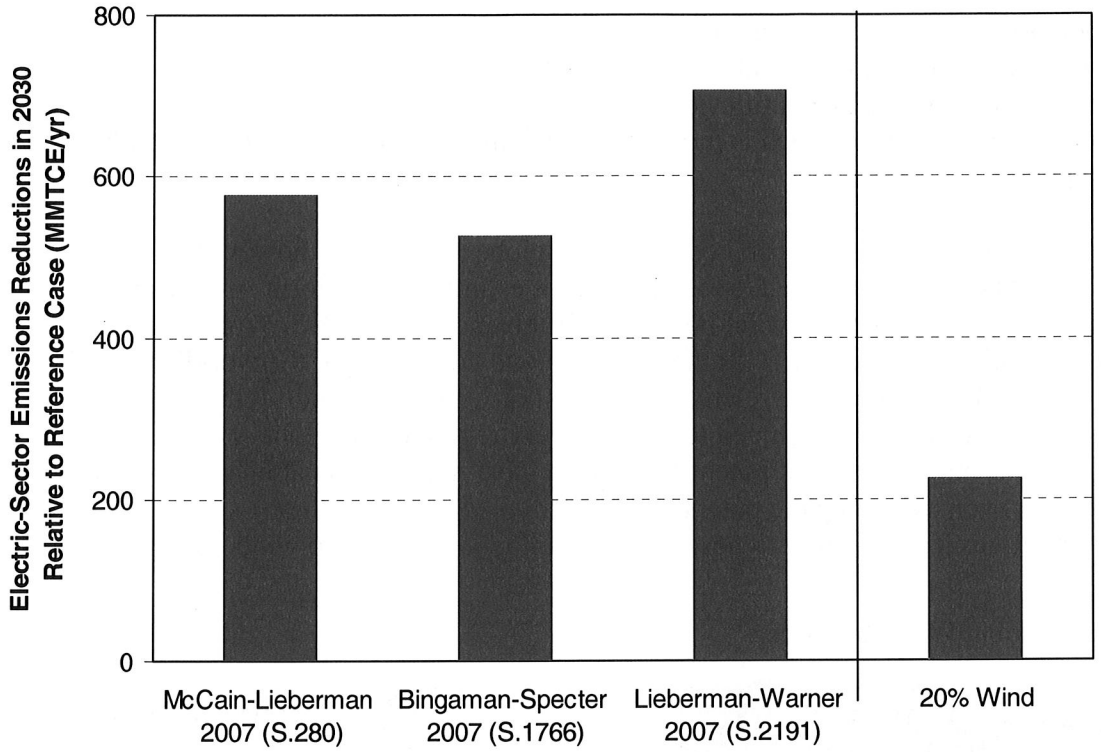
Figure 12. Carbon Emissions Reductions Associated with 20% Wind Penetration



Source: US DOE (2008)

To put that figure in context, several legislative proposals were considered in the 110th US Congress to limit economy-wide greenhouse gas emissions. The Energy Information Administration evaluated three of these proposals (EIA 2007, 2008a, 2008b), finding that emissions reductions would come *primarily* from the electric power sector, and that electric-sector emissions in 2030 would fall to just *15-60%* of 2005 levels. As shown in Figure 13, the annual emissions reductions predicted to come from the 20% Wind scenario in 2030 represent a substantial down-payment towards even these aggressive emissions reduction targets.

Figure 13. Comparing the Carbon Savings from 20% Wind to Proposed US Climate Legislation



Source: Compiled by Berkeley Lab based on EIA (2007, 2008a, 2008b)

Moreover, it appears that the 20% Wind scenario represents a relatively low-cost option for reducing carbon emissions. If one allocates the full predicted incremental cost of achieving 20% wind ($40 billion plus) to the carbon savings predicted above, for example, one finds that the 20% Wind scenario yields carbon reductions at under $13/tCO2-eq.[15] This figure is below the $20-80/tCO2-eq carbon price range that the IPCC (2007a) reports may be necessary by 2030 to achieve 550 ppm stabilization by 2100[16], and is also lower than the carbon prices of roughly $25-60/tCO2-eq predicted by the EIA to be required in 2030 under climate legislation proposed during the 110th US Congress (EIA 2007, 2008a, 2008b).

[15] Even in the more-conservative cases presented by Blair et al. (2008), carbon reduction costs rarely exceed $30/tCO2-eq.

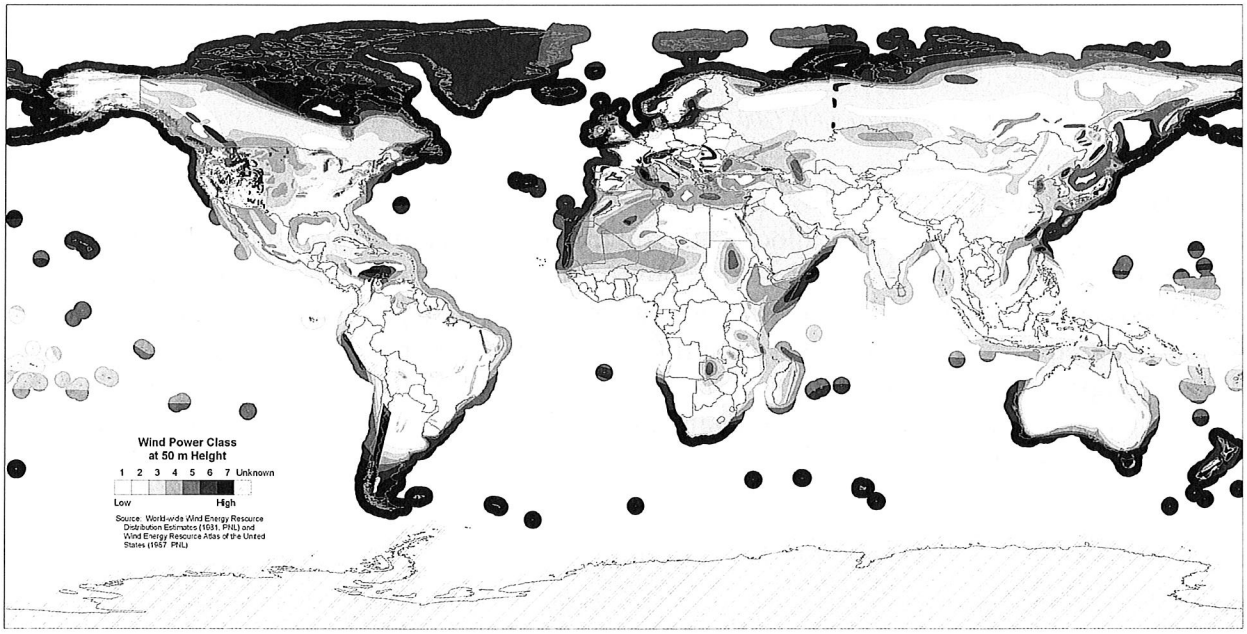
[16] With induced technology changes, the IPCC reports prices from $5-65/tCO2-eq. Again note that some governments and scientists have called for carbon stabilization at well below 550 ppm, presumably requiring even higher carbon prices.

The Potential Global Role of Wind Power

The US is not alone in its potential for substantial increases in wind power supply. In fact, a growing number of studies have sought to document the world's wind resources. Reporting on other studies, the IPCC (2007b) identifies an aggregate worldwide onshore wind power potential of roughly 600 Exajoules (EJ), which is more than three times greater than current worldwide electricity supply.[17]

The wind resource is not evenly distributed across the globe (Figure 14), however, and North America is particularly well endowed; two studies have estimated that North America hosts roughly 25% of the global onshore wind potential (Grubb and Meyer 1993; World Energy Council 1994), while another study finds that the US alone holds 22% of the world's potential (Hoogwijk et al. 2004). As such, the relatively low cost of wind as a carbon-reduction strategy for the US should not simply be assumed to hold in every region of the globe (Hoogwijk et al. 2004). Nonetheless, ample technical potential exists in most regions to enable high levels of wind penetration, even excluding the potential for offshore wind. As such, the size of the resource potential, itself, is unlikely to pose a significant *global* barrier to wind power expansion

Figure 14. The Global Wind Resource



The US is also not alone in conducting analyses of the feasibility of achieving higher levels of wind power deployment. In part relying on the resource data presented above, analyses of the technical and economic feasibility of achieving high levels of wind power penetration have been

[17] Studies that have been conducted on the world's wind resource potential include: Archer and Jacobsen (2005), Fellows (2000), Grubb and Meyer (1993), Hoogwijk et al. (2004), World Energy Council (1994), and WBGU (2004). Recent studies have often found an onshore wind resource potential that exceeds that reported by the IPCC (2007b); the IPCC figure also excludes offshore wind energy, which would add to the technical potential estimates.

conducted in a number of countries and regions,[18] as well as globally, using a diverse set of analytic tools and methods. A sample of recent global scenarios is summarized in Table 4.[19]

Table 4. Recent Global Wind Energy Deployment Scenarios

Study Sponsors	Wind Power as Proportion of Global Electricity Supply
IPCC (2007b)	7% by 2030
IEA (2007)*	8.4% by 2030
IEA (2008)	9% (ACT Map scenario) or 12% (BLUE Map scenario)
European Commission (2006)**	13% by 2050
Edmonds et al. (2007)***	14% by 2035
Shell (2008)****	23% by 2050
WBGU (2004)*	135 EJ by 2040 (13% of total energy supply)
Greenpeace and EREC (2007)	23% by 2050
Greenpeace and GWEC (2006)*****	11-18% (moderate) or 21-34% (advanced) by 2050
Greenpeace and EWEA (2005)	12% by 2020

* 450 ppm carbon stabilization case
** Carbon constraint scenario
*** 550 ppm carbon stabilization scenario; penetration levels increase to 2095
**** Approximate percentage for "Blueprints" scenario
***** Penetration range within single scenario depends on assumed degree of energy efficiency

The range of approaches used to generate these scenarios is great, making any comparison of the scenarios suspect. Additionally, as noted earlier, existing modeling tools often do a relatively poor job at estimating the technical and economic viability of high levels of wind penetration, due to the geographic and temporal characteristics of wind potential and production. As such, the global scenarios presented here should be considered – at best – indicative of wind's potential, and should not be used as an estimate of the "optimal" or "maximum" level of wind production that might be feasible on a global basis.

Nonetheless, the summary of these scenarios provided in Table 4 suggests that wind penetration levels that approach 10% of global electricity supply by 2030 are feasible, and that aggressive policies and/or technology improvements may allow wind production to ultimately reach 20% or more of global supply. As with the US DOE analysis presented earlier, most of these scenarios are not predicated on the widespread use of electricity storage to manage wind's inherent variability. Other strategies (e.g., flexible, fast-ramping combustion turbines) can also be used to manage wind's variability, and storage will have to compete with these options. If wind penetration levels exceed 10-20%, however, complementary storage technologies may be required to minimize cost. [20] Even at lower penetration levels, the availability of storage can ease

[18] In this book, for example, Chapter Y provides an assessment of the possible role of wind power (among other technologies) in meeting China's energy needs in both a business-as-usual and carbon-constrained future, while other chapters include some discussion of the role in wind in the UK (Chapter Z) and New Zealand (Chapter Y).
[19] For reviews of the renewable energy scenario literature more broadly, see Martinot et al. (2007) and Hamrin et al. (2007).
[20] At higher levels of wind penetration, wind output may need to be curtailed during some portion of the year. At this point, the value of storage increases significantly. A variety of studies have looked at wind power penetrations

the burden of integrating wind into electric power grids, though storage should only be deployed for this purpose if it is economical to do so relative to other integration strategies.

Pacala and Socolow (2004) and Socolow and Pacala (2006) describe a simplified scenario that may enable carbon dioxide stabilization at 500 ppm, initially requiring the displacement of 175 billion tons of carbon (GtC) over 50 years, or seven "wedges" of 25 GtC each. Though decomposing the carbon problem into such "wedges" has limitations, it nonetheless provides a useful heuristic for highlighting the importance of different technology solutions – including wind – in combating global climate change. In particular, the high-penetration wind power studies presented in this chapter suggest that wind power may be able to deliver one of these seven wedges in the medium term. Specifically, assuming that the 20% Wind scenario presented earlier for the United States achieves and then maintains 305 GW of wind from 2030-2050, that scenario is estimated to deliver more than 6 GtC emissions reduction through 2050, and to do so at a cost below many other carbon reduction strategies. By 2030, the US electricity sector is expected to represent roughly 18% of global electricity generation. By simple extrapolation, if the world was also able to achieve a similar 20% wind penetration level, then global cumulative carbon emissions reductions from wind would exceed the size of a single 25 GtC wedge.[21]

Conclusions

The challenge of supplying energy reliably, securely, and economically, while also tackling the threat of climate change, is daunting. In concert with other technologies, however, wind power is ready today to begin confronting this challenge. Global wind resource potential is vast and, though accessing this potential is not costless or lacking in barriers, wind power can be developed at what many would consider to be an acceptable cost.

To grow wind at scale, however, a "business as usual" path will not do. In addition to the common needs of other low-carbon technologies, such as stable, long-term promotional policies and placing an economic price on carbon emissions, the following actions are likely to be needed:

1. Dramatically expanded transmission investments specifically designed to access remote wind resources.
2. Larger power control regions, better wind forecasting, and increased investment in fast-responding generating plants to more-effectively integrate wind power into electricity grids.
3. Streamlined siting and permitting procedures that allow developers to identify appropriate project locations and move from wind resource prospecting to project construction quickly.

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in excess of 20% in certain regions, typically involving the use of storage, plug-in hybrid vehicles, demand response, and/or other technologies to manage the variability of wind power. For a sample of recent (and in some cases somewhat US-centric) examples, see: Benitez et al. (2008), Black and Strbac (2006), Cavallo (2007), DeCarolis and Keith (2006), Denholm (2006), Hoogwijk et al. (2007), Greenblatt et al. (2007), Kempton and Tomic (2005), Lund and Kempton (2008), and Leighty (2008).

[21] Clearly, this is a crude approach, as it assumes that the fossil generation offset by worldwide wind additions is similar to that estimated for the United States, and it ignores possible interactions between carbon reduction strategies. Nonetheless, the estimates provided here are reasonably consistent with the wind electricity wedge posited by Pacala and Socolow (2004) and Socolow and Pacala (2006).

4. Enhanced research and development to lower the cost of offshore wind power, and incrementally improve conventional onshore wind technology.
5. Investments in technologies and practices that may enable even greater penetration of wind, including storage, plug-in hybrids, demand response, and hydrogen production.

Long ago, Henry David Thoreau wrote: "First, there is the power of the Wind, constantly exerted over the globe… Here is an almost incalculable power at our disposal, yet how trifling the use we make of it. It only serves to turn a few mills, blow a few vessels across the ocean, and a few trivial ends besides. What a poor compliment do we pay to our indefatigable and energetic servant!"[22] More than a century-and-a-half later, we are now able to both calculate and efficiently utilize the power in the wind – perhaps it is finally time to lean more heavily on this "indefatigable and energetic servant."

Acknowledgements

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References

Archer, C. and M. Jacobsen. 2005. "Evaluation of Global Wind Power." *Journal of Geophysical Research*, 110, D12110.

Benitez, L., P. Benitez and G. van Kooten. 2008. "The Economics of Wind Power with Energy Storage." *Energy Economics*, 30: 1973-1989.

Black, M. and G. Strbac. 2006. "Value of Storage in Providing Balancing Services for Electricity Generation systems with High Wind Penetration." *Journal of Power Sources*, 62: 949-953.

Blair, N., M. Hand, W. Short, and P. Sullivan. 2008. "Modeling Sensitivities to the 20% Wind Scenario Report with the WinDS Model." NREL/CP-670-43511. Conference paper: WINDPOWER 2008. Houston, Texas.

BTM Consult. 2008. "International Wind Energy Development: World Market Update 2007." Ringkobing, Denmark: BTM Consult.

Cavallo, A. 2007. "Controllable and Affordable Utility-Scale Electricity from Intermittent Wind Resources and Compressed Air Energy Storage (CAES)." *Energy*, 32: 120-127.

[22] Henry David Thoreau. "Paradise (To Be) Regained" (1843), in The Writings of Henry David Thoreau, vol. 4, pp. 286-287, Houghton Mifflin (1906).

Chupka, M. and G. Basheda. 2007. "Rising Utility Construction Costs: Sources and Impacts." Prepared by The Brattle Group for The Edison Foundation.

Cryts, J., A. Derkach, S. Nyquist, K. Ostrowski and J. Stephenson. 2007. "Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?" McKinsey & Company.

DeCarolis, J. and D. Keith. 2006. "The Economics of Large-Scale Wind Power in a Carbon Constrained World." *Energy Policy*, 34: 395-410.

Denholm, P. 2006. "Improving the Technical, Environmental, and Social Performance of Wind Energy Systems Using Biomass-Based Energy Storage." *Renewable Energy*, 31: 1355-1370.

de Vries, B., D. van Vuuren and M. Hoogwijk. 2007. "Renewable Energy Sources: Their Global Potential for the First-Half of the 21st Century at a Global Level: An Integrated Approach." *Energy Policy*, 35: 2590-2610.

Edmonds, J., M. Wise, J. Dooley, S. Kim, S. Smith, P. Runei, L. Clarke, E. Malone ands G. Stokes. 2007. "Global Energy Technology Strategy: Addressing Climate Change." Phase 2 Findings from an International Public-Private Sponsored Research Program. College Park, Maryland: Joint Global Change Research Institute.

Emerging Energy Research (EER). 2008. "Wind Turbine Industry Steps Up to Global Demand." Emerging Energy Research press release on Global Wind Turbine Markets and Strategies 2008-2020.

Energy Information Administration (EIA). 2007. "Energy Market and Economic Impacts of S. 280, the Climate Stewardship and Innovation Act of 2007." SR/OIAF/2007-04. Washington, D.C.: Energy Information Administration.

Energy Information Administration (EIA). 2008a. "Energy Market and Economic Impacts of S. 1766, the Low Carbon Economy Act of 2007." SR/OIAF/2007-06. Washington, D.C.: Energy Information Administration.

Energy Information Administration (EIA). 2008b. "Energy Market and Economic Impacts of S.2191, the Lieberman-Warner Climate Security Act of 2007." SR/OIAF/2008-01. Washington, D.C.: Energy Information Administration.

European Commission. 2006. "World Energy Technology Outlook - 2050 - WETO H2." Brussels, Belgium: European Commission.

European Wind Energy Association (EWEA). 2008. "Pure Power: Wind Energy Scenarios up to 2030." Brussels, Belgium: European Wind Energy Association.

Fellows, A. 2000. "The Potential of Wind Energy to Reduce Carbon Dioxide Emissions." Glasgow, UK: Garrad Hassan.

Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagan, M. Raymo, D. Royer and J. Zachos. 2008. "Target Atmospheric CO2: Where Should Humanity Aim?" Submission to *Open Atmospheric Science Journal*, last revised June 2008: arXiv:0804.1126v2.

Global Wind Energy Council (GWEC). 2008. "Global Wind 2007 Report." Brussels, Belgium: Global Wind Energy Council.

Greenblatt, J., S. Succar, D. Denkenberger, R. Williams and R. Socolow. 2007. "Baseload Wind Energy: Modeling the Competition Between Gas Turbines and Compressed Air Energy Storage for Supplemental Generation." *Energy Policy*, 35: 1474-1492.

Greenpeace and Global Wind Energy Council (GWEC). 2006. "Global Wind Energy Outlook 2006." Amsterdam, The Netherlands and Brussels, Belgium.

Greenpeace and European Renewable Energy Council (EREC). 2007. "Energy [R]evolution: A Sustainable World Energy Outlook." Amsterdam, The Netherlands and Brussels, Belgium.

Greenpeace and European Wind Energy Association (EWEA). 2005. "Wind Force 12: A Blueprint to Achieve 12% of the World's Electricity from Wind Power by 2020." Prepared for the Global Wind Energy Council.

Gross, R., P. Heptonstall, M. Leach, D. Anderson, T. Green and J. Skea. 2007. "Renewables and the Grid: Understanding Intermittency." *Energy,* 160: 31-41.

Grubb, M. and N. Meyer. 1993. "Wind Energy: Resources, Systems, and Regional Strategies." Chapter 4 in T. Johansson, H. Kelly, A. Reddy and R. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity*. Washington, DC: Island Press.

Haas, R., N. Meyer, A. Held, D. Finon, A. Lorenzoni, R. Wiser and K. Nishio. 2008. "Promoting electricity from renewable energy sources – lessons learned from the EU, U.S. and Japan." Chapter 12 in F. Sioshansi (ed.), *Competitive Electricity Markets: Design, Implementation, Performance.* Oxford, UK: Elsevier.

Hamrin, J., H. Hummel and R. Canapa. 2007. "Review of the Role of Renewable Energy in Global Energy Scenarios." Prepared for the International Energy Agency Implementing Agreement on Renewable Energy Technology Deployment. San Francisco, California: Center for Resource Solutions.

Hoogwijk, M. 2004. "On the Global and Regional Potential of Renewable Energy Sources." Utrecht, The Netherlands: Utrecht University.

Hoogwijk, M., B. de Vries and W. Turkenburg. 2004. "Assessment of the Global and Regional Geographic, Technical and Economic Potential of Onshore Wind Energy." *Energy Economics*, 26: 889-919.

Hoogwijk, M., D. van Vuuren, B. de Vries and W. Turkenburg. 2007. "Exploring the Impact on Cost and Electricity Production of High Penetration Levels of Intermittent Electricity in OECD Europe and the USA, Results for Wind Energy." *Energy*, 32: 1381-1402.

Husum WindEnergy (Husum). 2008. "WindEnergy Study 2008: Assessment of the Wind Energy Market Until 2017." Prepared by Messe Husum in cooperation with Hamburg Messe on behalf of Husum WindEnergy.

International Energy Agency (IEA). 2007. "World Energy Outlook 2007." Paris, France: International Energy Agency.

International Energy Agency (IEA). 2008. "Energy Technology Perspectives 2008: Scenarios & Strategies to 2050." Paris, France: International Energy Agency.

Intergovernmental Panel on Climate Change (IPCC). 2007a. "Climate Change 2007: Synthesis Report." Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change (IPCC). 2007b. "Climate Change 2007: Mitigation." Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, United States: Cambridge University Press.

Johansson, T., K. McCormick, L. Neij and W. Turkenburg. 2004. "The Potentials of Renewable Energy." Thematic Background Paper for International Conference for Renewable Energies, Bonn 2004.

Kempton, W. and J. Tomic 2005. "Vehicle-to-Grid Power Implementation: From Stabilizing the Grid to Supporting Large-Scale Renewable Energy." *Journal of Power Sources*, 144: 280-294

Key, T. 2007. "Role of Renewable Energy in a Sustainable Electric Generation Portfolio." Presentation to EIA Energy Outlook, Modeling, and Data Conference. 28 March. Washington, D.C.

Kutscher, C. (ed.). 2007. "Tackling Climate Change in the U.S.: Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030." American Solar Energy Society.

Kyle, P., S.J. Smith, M.A. Wise, J.P. Lurz and D. Barrie. 2007. "Long-Term Modeling of Wind Energy in the United States." PNNL-16316. College Park, Maryland: Joint Global Change Research Institute, College Park.

Leighty, W. 2008. "Running the World on Renewables: Hydrogen Transmission Pipelines and Firming Geologic Storage." *International Journal of Energy Research*, 32: 408-426.

Lewis, J. and R. Wiser. 2006. "Fostering a Renewable Energy Technology Industry: An International Comparison of Wind Industry Policy Support Mechanisms." *Energy Policy,* 35(3): 1844-1857.

Lund, H. and W. Kempton. 2008. "Integration of Renewable Energy Into the Transport and Electricity Sectors Through V2G." *Energy Policy*, 36: 3578-3587.

Martinot, E., C. Dienst, L. Weiliang and C. Qimin. 2007. "Renewable Energy Futures: Targets, Scenarios, and Pathways." *Annual Review of Environment and Resources*, 32: 205-239.

Mendonca, M. 2007. Feed-*in Tariffs: Accelerating the Deployment of Renewable Energy.* London, UK: Earthscan.

Meyer, N. 2007. "Learning from Wind Energy Policy in the EU: Lessons from Denmark, Germany and Spain." *European Environment*, 17 (5): 347-362.

Neuhoff, K., A. Ehrenmann, L. Butler, J. Cust, H. Hoexter, K. Keats, A. Kreczko and G. Sinden. 2008. "Space and Time: Wind in an Investment Planning Model." *Energy Economics*, 30: 1900-2008.

Pacala, S. and R. Socolow. 2004. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science*, 305 (5686): 968-972.

REN21. 2007. "Renewable Energy Potentials: Opportunities for the Rapid Deployment of Renewable Energy in Large Energy Economies." Intermediate Report to the 3rd Ministerial Meeting of the Gleneagles Dialog on Climate Change, Clear Energy and Sustainable Development. Paris, France: REN21 Secretariat.

REN21. 2008. "Renewables 2007 Global Status Report." Paris, France: REN21 Secretariat.

Shell. 2008. "Shell Energy Scenarios to 2050." The Hague, The Netherlands: Shell International.

Short, W., N. Blair and D. Heimiller. 2004. "Projected Impact of Federal Policies on U.S. Wind Market Potential." *Proceedings of the 2004 Global Wind Power Conference*. 29-31 March. Chicago, Illinois.

Smith, J.C., M. Milligan, E. DeMeo and B. Parsons. 2007. "Utility Wind Integration and Operating Impact State of the Art." *IEEE Transactions On Power Systems*, 22 (3): 900-908.

Socolow, R. and S. Pacala. 2006. "A Plan to Keep Carbon in Check." *Scientific American*, 295 (3): 50-57.

Sullivan, P., W. Short and N. Blair. 2008. "Modeling the Benefits of Storage Technologies to Wind Power." NREL/CP-670-43510. Conference paper: WINDPOWER 2008. Houston, Texas.

United Nations Development Programme (UNDP). 2000. "World Energy Assessment: Energy and the Challenge of Sustainability." New York, United States: United Nations Development Programme.

US Department of Energy (DOE). 2008. "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply." DOE/GO-102008-2567. Washington, D.C.: U.S. Department of Energy.

van der Linden, N.H., M.A. Uyterlinde, C. Vrolijk, L.J. Nilsson, J. Khan, K. Åstrand, K. Ericsson, and R. Wiser. 2005. "Review of International Experience with Renewable Energy Obligation Support Mechanisms." Energy Centre of the Netherlands. ECN-C-05-025.

German Advisory Council on Global Change (WBGU). 2004. "World in Transition: Towards Sustainable Energy Systems." London, England and Sterling, Virginia: Earthscan.

Wiser, R., M. Bolinger and G. Barbose. 2007. "Using the Federal Production Tax Credit to Build a Durable Market for Wind Power in the United States." *The Electricity Journal*, 20 (9): 77-88.

Wiser, R. and M. Bolinger. 2008. "Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007." DOE/GO-102008-2590. Washington, D.C.: U.S. Department of Energy.

World Energy Council. 1994. "New Renewable Energy Resources: A Guide to the Future." London, UK: Kogan Page Limited.

World Energy Council. 2007. "2007 Survey of Energy Resources." London, UK: World Energy Council.

Text For Introduction

In **chapter 10**, **Ryan Wiser** and **Maureen Hand** describe the potential contribution of wind power in combating the inexorable rise in carbon emission. The global wind power market has been growing at a phenomenal pace in recent years, driven by favorable policies towards renewable energy and the improving economics of wind projects. But, how much more wind power can be expected, how soon, and at what ultimate cost?

Drawing upon a number of studies, the authors conclude that wind power is ready today for significant additional scale-up, thereby reducing the carbon footprint of the electricity sector. The technology has matured, and costs are, in good resource regimes, comparable to fossil-fuel generation. As such, the authors contend that the global wind resource is vast and, though accessing this potential is not costless or lacking in barriers, that wind power can be developed at scale in the near to medium term at what appears to be an acceptable cost.