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High Wind Penetration Impact on U.S. Wind Manufacturing Capacity and Critical Resources

Technical Report
NREL/TP-500-40482
October 2006

A. Laxson, M.M. Hand, and N. Blair

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Executive Summary

We used two different models to analyze a number of alternative scenarios of annual wind power capacity expansion to better understand the impacts of high levels of wind-generated electricity production on wind energy manufacturing and installation rates. The results of these approaches indicate that achieving levels of wind penetration of 20% of national electrical energy demand in the 2020 to 2030 time frame is possible without overwhelming the ability of U.S. industry to meet these demands.

These evaluations have looked at volumes of wind turbine production and changes in volume of production, as well as wind energy manufacturing impact on the supply of critical materials such as steel, fiberglass, rare earth permanent magnets, and copper. The analysis presented here also shows that the land area required for 300 GW of wind turbines, which would supply about 20% of the nation's projected electricity demand in 2020, equates to less than 1% of the contiguous U.S. land area (excluding Hawaii and Alaska), and less than 2% of that area would be physically occupied by turbines, roads, and other equipment.

These wind turbines would be geographically dispersed across the nation. From the perspective of manufacturing growth and material requirements, this study indicates that achieving a goal of 20% of U.S. energy demand from wind by 2020 may be feasible but that it requires a large increase in manufacturing that may create substantial excess capacity. Achieving 20% energy production from wind by 2030 requires manufacturing levels that appear to be more sustainable, with less risk of overcapacity. The exact mechanisms for stimulating this growth require further study.

1.0 Introduction and Background

Wind energy installations have increased dramatically worldwide over the past decade, primarily in Europe. Installations in the United States have been erratic in response to repeated expirations and renewals of the Production Tax Credit (PTC) (see Figure 1). The amount of the credit is adjusted for inflation such that in 2006 the federal PTC is $0.019/kWh for 10 years from the date of turbine installation. When active (2001 and 2003), this incentive stimulates growth in the number of wind turbine installations. When expired (parts of 2002 and 2004), the number of installations dwindles with the expectation of a renewal. In Europe, however, consistent policies have enabled consistent growth in the industry.

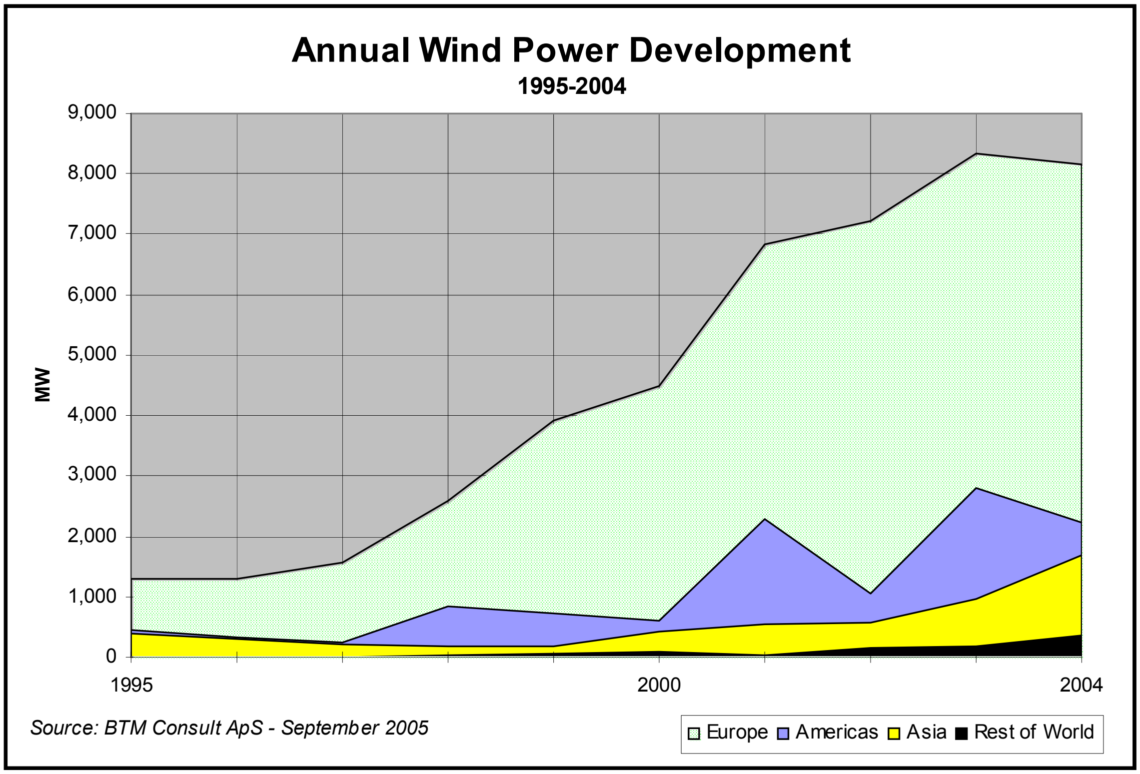


Figure 1. Annual wind power installations, 1995–2004 (BTM Consult ApS 2005)

During 2004, the 454 MW of wind turbines installed in the United States were supplied by GE Wind (48.9%), Mitsubishi (30.8%), and Vestas (20.3%) according to BTM Consult ApS (2005). BTM Consult ApS also reports that of the top 10 global suppliers in 2004, only GE Wind has manufacturing facilities in the United States. Much of the annual installed capacity of wind turbines in the United States is manufactured elsewhere.

This study assumes a consistent U.S. policy environment that supports investment in manufacturing facilities to supply a strong U.S. market. This study does not explore the myriad policy options that could create such an environment, but. focuses on the physical requirements such as manufacturing capacity increase and material quantities to support significant wind energy electricity generation in the United States.

As shown in Figure 1, the annual global wind turbine supply is less than 9 GW. The scenarios in this study require annual U.S. wind turbine installations greater than 20 GW/year to reach electricity generation levels of 20% or more. If the United States were committed to reaching significant wind energy penetration levels, global manufacturing capacity must increase significantly. Other countries are also considering significant expansions in wind turbine electricity generation, which would require additional manufacturing capacity. For simplicity this study assumes that the additional installed capacity to supply wind electricity generation in the United States is also manufactured in the United States.

2.0 Approach

Two approaches were used to explore the manufacturing capacity expansion and resource requirements for high wind penetration in the U.S. electricity market:.

- A simple Sustained Manufacturing Model was developed to identify the wind turbine manufacturing capacity that would be required to achieve electricity generation levels of 10%, 20%, and 30% of projected national electricity demand by 2020 or 2030. This model is based on prescribed manufacturing capacity increases that reflect past installation levels in the U.S. wind industry as well as typical growth expectations for heavy manufacturing industries.

- The Wind Deployment System (WinDS) Model, a multiregional, multi-time period, geographic information system and linear programming model of capacity expansion in the electric sector of the United States, developed by Short et al. (2003), was used to explore the sensitivity of wind development to policy incentives. WinDS was used to explore variations of the federal PTC incentive to ascertain associated wind-generated electricity market penetration levels by 2020.

  WinDS is designed to address the principal market issues related to the penetration of wind energy technologies into the electricity sector. These issues include access to and cost of transmission and the variability of wind power. (WinDS performs a detailed examination of the capacity value of wind energy, the required operating reserve and the wind surplus using the annual average capacity factor.) WinDS resembles the National Energy Modeling System (NEMS) that is maintained and developed by the Energy Information Administration (EIA) in that it is a linear optimization model, but it varies significantly from NEMS—most obviously through greater geographic diversity and that WinDS only deals with the electric sector.

  The PTC is set to expire December 31, 2007. Currently, it is adjusted for inflation, but the cases modeled with WinDS extend the 2002 value of $0.018/kWh forward in time without inflation adjustment. In addition to the base case, which assumes currently enacted policy incentives, three variations of the PTC were explored: extension through 2020, extension through 2010 with linear decline to zero after 2020, and linear decline to zero after 2020.

The purpose of this study is to identify potential gross barriers, such as manufacturing rates or resource limitations, which would prohibit near-term high wind energy penetration levels in the U.S. electricity market. Although the WinDS model does account for the cost of adding new transmission and the intermittency impacts at high penetration levels, this study does not explore potential barriers related to transmission construction lead time or wind farm permitting and site selection other than via typical resource exclusions (state and federal lands designated as parks, wilderness, national monuments, recreation areas, wildlife areas, urban corridors, etc.). This study also does not consider potential electricity demand increases associated with shifting transportation needs to the electricity sector or significant reductions that result from energy efficiency gains. Finally, this study does not explore the overall composition of electricity generation technologies that supply the nation's demand, e.g., the contribution to the nation's electricity supply from traditional fossil fuels, nuclear, or other renewable technologies.

Projected electricity demand in 2020 and 2030 is published by the EIA in the *Annual Energy Outlook* (AEO) 2006 (EIA 2006). Assuming wind turbine technology is consistent with the DOE Wind Program Low Wind Speed Technology (LWST) 2002 baseline (1.5-MW turbine, 70-m rotor diameter, 65-m hub height, 33.4% capacity factor, which produces 2.92 billion kWh/GW of installed capacity), the installed wind capacity necessary to meet 10%–40% of the projected electrical energy demand is shown in Table 1. The subsequent number of turbines based on a 1.5-MW platform and a 3-MW platform is also shown. This LWST baseline with its 70-m rotor, 65-m hub height and predicted coefficient of power (C_p) of 0.47 is conservative. Many 1.5-MW machines now have rotors of up to 77 m and operate at hub heights of up to 80 m. They also operate with C_p of 0.5. All these factors significantly increase the performance and capacity factor of a turbine. Also, these calculations assume all machines are identical and operate in Class 4 winds. However, the same turbine in a higher class wind would have a higher capacity factor. Turbine technology advancements are likely to continue to increase turbine size to 3-MW or possibly even 5-MW units over time, which reduces the total number of turbines that would be required to meet these energy penetration targets. Continued technological advancement, and potentially higher turbine hub heights, will improve the performance and increase the capacity factor. The Sustained Manufacturing Models do not reflect any technology advancements to be conservative, but the WinDS model does assume technology advancements projected by the DOE Wind Program (NREL 2006). This explains the differing installed capacity (gigawatts) to meet similar electricity generation percentages.

Table 1. Energy Generation and Installed Wind Capacity to Achieve Penetration Targets*

	2020				2030			
	Energy generation (billion kWh)	Wind Capacity (GW)	Number of 1.5 MW Turbines	Number of 3 MW Turbines	Energy generation (billion kWh)	Wind Capacity (GW)	Number of 1.5 MW Turbines	Number of 3 MW Turbines
10%	489.3	167.6	111,712	55,856	564.8	193.4	128,950	64,475
20%	978.6	335.1	223,425	111,712	1129.6	386.8	257,900	128,950
30%	1467.9	502.7	335,137	167,568	1694.4	580.3	386,849	193,425
40%	1957.2	670.3	446,849	223,425	2259.2	773.7	515,799	257,900

*Based on AEO 2006 reference case projected U.S. energy requirements and LWST baseline turbine technology in Class 4 wind regimes (2.92 billion kWh/GW of machine rating or 33.3% capacity factor).

3.0 2020–2030 Sustained Manufacturing Models

A wind farm is designed for a lifetime of 20 to 30 years, after which repowering is required. Figure 2 illustrates projected installed capacity for Germany for onshore and offshore turbines as well as projected repowering requirements. The onshore projections show a sharp peak of installed capacity exceeding 3000 MW in 2003, followed by a shallower peak of onshore repowering capacity of about 2000 MW from 2018 to 2023. The total projected installed capacity for 2008 is about 1200 MW. Future repowering needs mirror the installation pattern in the near term. For large increases in capacity, on the order of tens of gigawatts per year, sharp peaks in the near term will be followed by sharp declines. Another peak will then occur as the original installations begin to be repowered. Sustained Manufacturing Models were developed to determine annual installation levels that would minimize these fluctuations by approaching a level manufacturing capacity that meets repowering requirements and achieves a certain electricity generation percentage in a specified time frame.

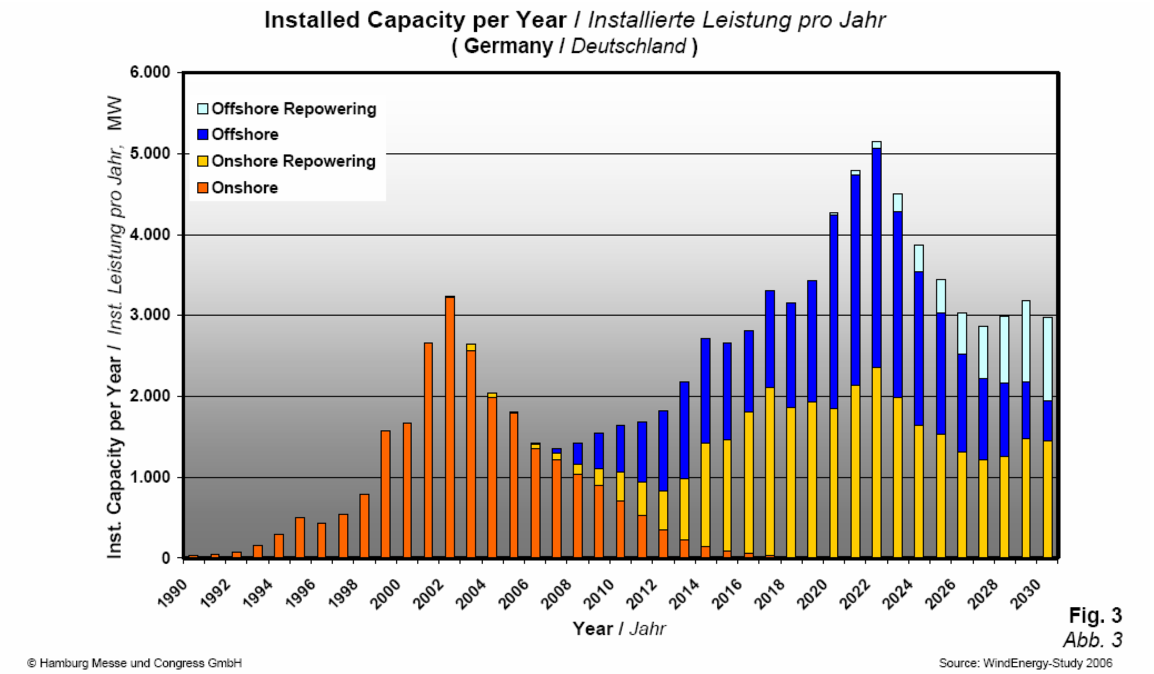


Figure 2. Projected wind energy installations for onshore and offshore turbines, including repowering, in Germany (Wind Energy-Study 2006).

The 2020 and 2030 Sustained Manufacturing Models were constructed in a spreadsheet to determine the level of wind turbine manufacturing capacity required to meet grid electricity generation goals of 10%, 20%, and 30% in 2020 and 2030 from wind energy. The AEO 2006 (EIA 2006) reference case provides the projected net electricity generation to the grid for each year from 2006 through 2030. After 2030, a growth rate of 1.5% is assumed. The LWST 2002 baseline was used to determine the amount of wind turbine capacity needed. The required energy generation capacity from LWST turbines to supply 10%, 20%, and 30% of the predicted net electricity generation to the grid was determined for each year from 2006 through 2060. This provided the target nameplate capacities for each penetration goal in 2020 and in 2030, as shown in Table 1. For simplicity, this model assumes that all turbine installations in the United States are manufactured in the United States.

The turbine nameplate capacity demand for each year from 2006 through 2060 was based on the maximum manufacturing capacity for a given year. A turbine lifetime of 25 years was assumed such that the nameplate capacity installed 25 years previously was assumed to be replaced. The rest of the manufacturing capacity was available for new installations. Historical installed capacity numbers (AWEA 2006) were used to estimate repowering needs for turbines installed between 1981 and 2005. The installed capacity in 2006 was assumed to be replaced completely in 2031. This continued for subsequent years such that the entire fleet was always replaced every 25 years, as shown in Figure 3 for the 20% generation by 2030 case.

Complete replacement of turbines at 25-year intervals is artificial. In reality, the repowering would be spread over several years, with some turbines replaced sooner and others replaced later. The sharp drops in demand in 2030 and 2055 would in reality be more gradual, but a dip would occur. The new generation capacity shown in this figure represents the increase in wind capacity required to sustain the electricity generation level of 20% in this case. This penetration is achieved in 2030, but additional capacity is needed to maintain that beyond 2030.

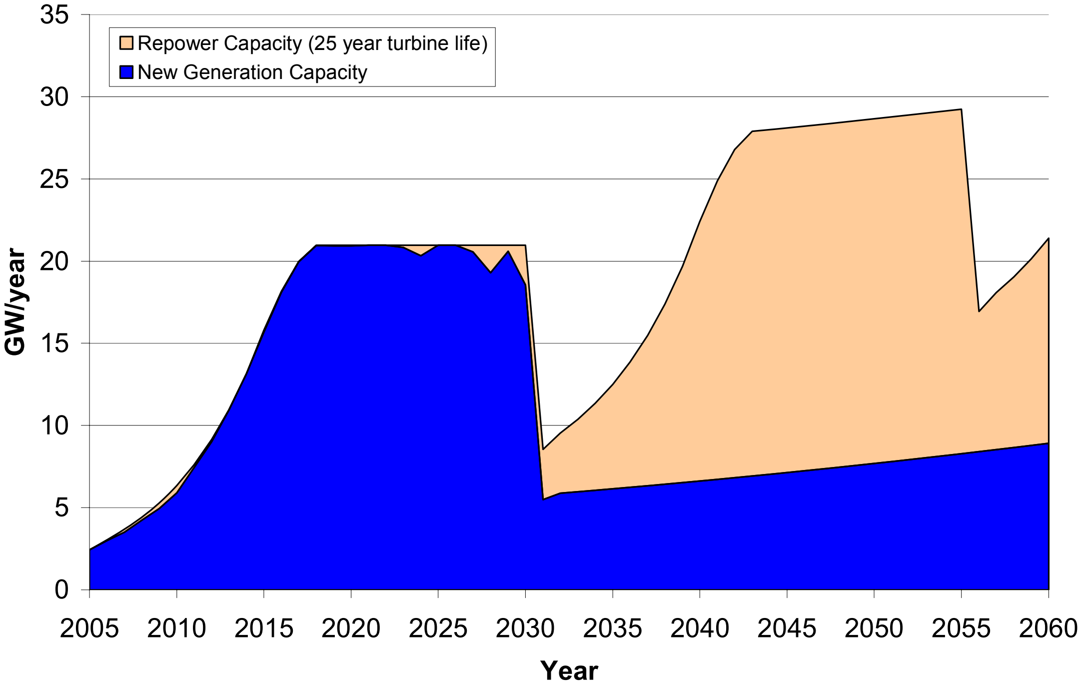


Figure 3. Wind turbine annual installed capacity required to meet projected load growth and repowering capacity corresponding to the Sustained Manufacturing Model 20% by 2030 scenario

The need for replacement after 25 years affects the desirable manufacturing level. Significant wind capacity must be installed to significantly increase wind energy penetration. If manufacturing capacity is developed quickly, e.g., in less than 10 years, and remains constant, there will be a 10-year period at 25-year intervals where the demand for new turbines in the United States is much less than the manufacturing capability. This type of expansion is shown in Figure 3. If manufacturing capacity is expanded quickly to a very high level, once the penetration goal is reached, the demand for new turbines will drop precipitously and leave significant manufacturing capacity idle. This type of installation pattern is represented by the onshore turbine installations for Germany shown in Figure 2, but the magnitude of the peaks and valleys could be much greater. Even though some of this manufacturing capacity could be targeted toward exports, wild swings in demand are probably unsustainable over the long term. The ideal situation would be to achieve a manufacturing capacity level that is high enough to achieve the penetration goal but not so high that plants are left idle. Such foresight and planning will be difficult to effect in a pure free market economy, and will cause inefficiencies and volatile prices.

The Sustained Manufacturing Models assume a manufacturing capacity increase of 34% in 2006 based on AWEA's estimated installed capacity of 3 GW for 2006 of the 9.149 GW installed by the end of 2005. An increase of 20% was conservatively projected for 2007. Some sort of that would stimulate aggressive manufacturing growth incentive was assumed to take effect in 2008. Based on AWEA's historical installed capacity increases, the last two growth spurts in 2003 and 2005 were about 36% each. The largest increase in one year (2001) was 66%. These increases represent installation increases rather than U.S. manufacturing increases. Manufacturing growth for heavy manufacturing industries at 20%–25% annually is considered high, but has been demonstrated by the global wind industry (Wind Force 12). Obviously, high levels of growth cannot be sustained indefinitely. These models predict the capacity increase and annual installation level required to achieve an electricity generation target in a prescribed time frame.

3.1 2020 Sustained Manufacturing Model

This model is, in effect, three scenarios. It describes the installation required to achieve 10%, 20%, and 30% of electrical energy demand by 2020. It also takes into account manufacturing to meet repowering requirements for a retired wind plant based on an assumed 25-year life. Annual manufacturing increases in the near term were prescribed for each scenario and result in the annual capacity levels shown in Figure 4. Manufacturing increases of 50% or 65% per year over three years must occur to meet electrical energy generation production of 20% or 30% by 2020. Reaching 10% of electrical energy generation by 2020 would require annual increases of 20%. Figure 5 illustrates the cumulative installed wind capacity that corresponds to these manufacturing levels, assuming all of the annual capacity continues to be installed each year beyond achievement of the penetration goal. The leveling of the installed capacity from 2036 through 2056 represents a shift in manufacturing capacity to replace plants that will be retired in that period. The black dashed lines represent projected wind nameplate capacity that corresponds to the 10%, 20%, and 30% electrical energy generation levels (assuming LWST turbine performance of 2.92 billion kWh/GW installed capacity, or 33.3% capacity factor). Assuming that manufacturing capacity is ramped up to a constant level and that turbines continue to be installed at the constant manufacturing capacity, penetration levels continue to increase over time. For instance, the manufacturing capacity required to achieve 20% electricity generation by 2020 (about 30 GW/year) would ultimately result in a penetration level greater than 30% in 2036 before repowering consumes most of the turbines manufactured in a given year.

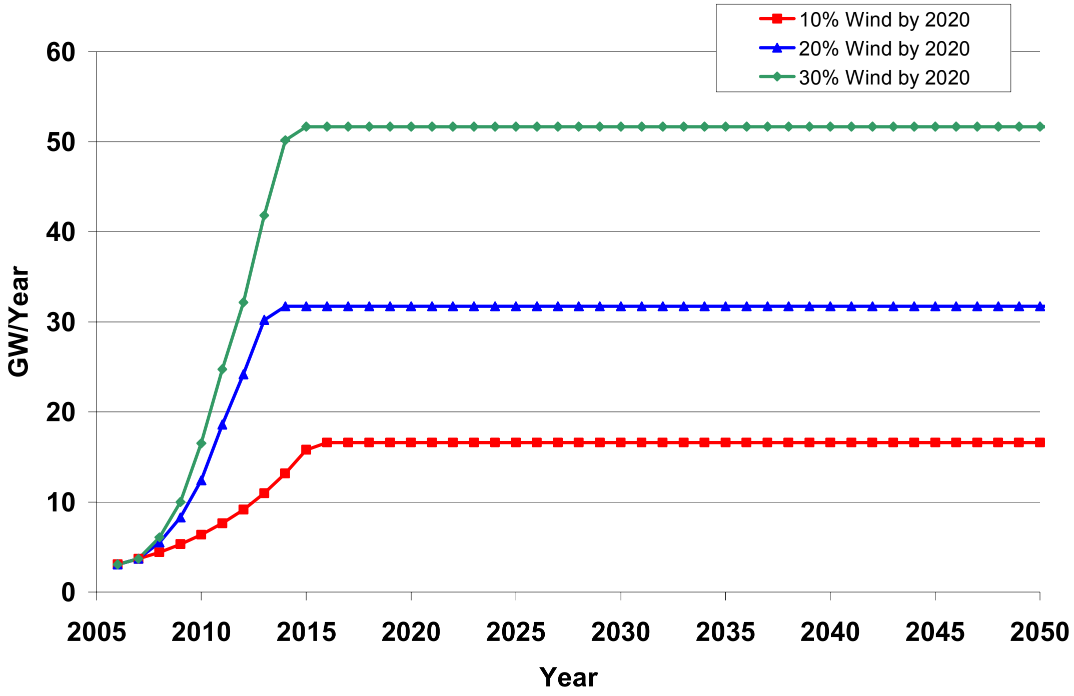


Figure 4. Manufacturing production level required to meet energy supply goals by 2020

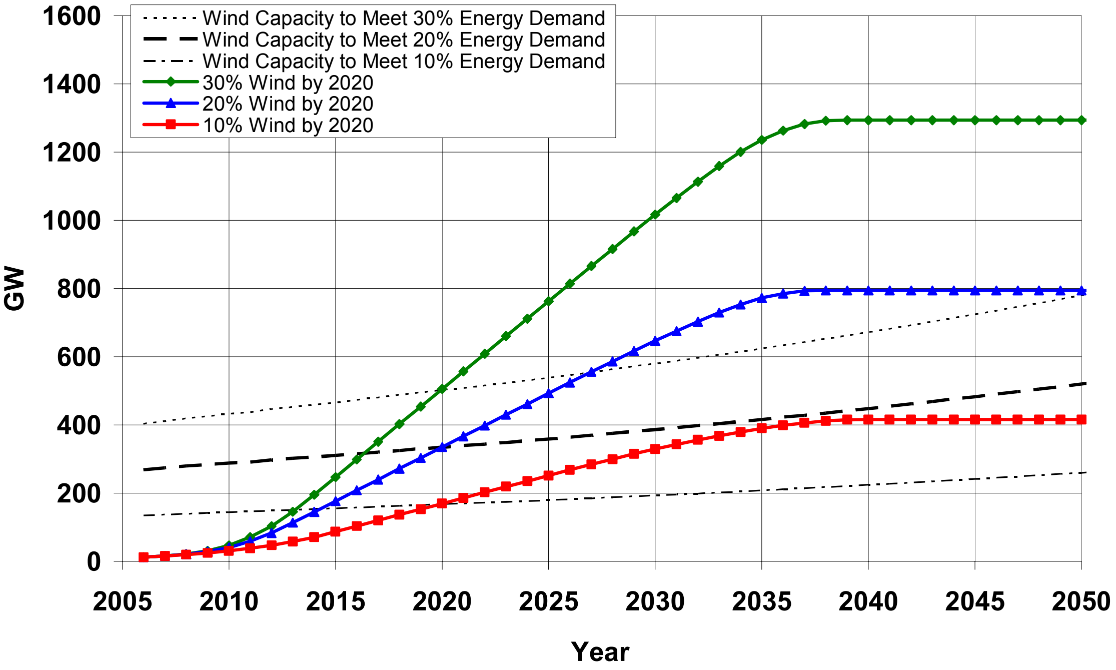


Figure 5. Cumulative wind generation capacity assuming production continues at maximum level after energy generation goals met in 2020

3.2 2030 Sustained Manufacturing Model

This model also consists of three scenarios. It describes the annual installation required to achieve 10%, 20%, and 30% of electrical energy demand by 2030 (see Figure 6). It also takes into account manufacturing to meet repowering requirements for retired wind plants. Achieving 30% electricity generation from wind by 2030 would require three years of annual installation increases of 30% followed by several years of annual increases of 20%. To achieve 20% electric generation by 2030, annual installation increases of 20% must be sustained for nearly a decade. Sustained annual increases of 10% would result in 10% electricity generation from wind by 2030. Figure 7 illustrates the cumulative installed capacity associated with the manufacturing levels shown in Figure 6. The black dashed lines in Figure 7 show the wind capacity required to meet 10%, 20% and 30% of the projected electricity demand (assuming LWST turbine performance of 2.92 billion kWh/GW installed capacity, or 33.3% capacity factor). The sustained manufacturing level required to achieve 20% energy demand by 2030 (about 20 GW/year) results in a penetration level slightly more than 20% in 2040. Repowering efforts require the annual manufacturing capacity beyond 2050 such that the penetration level remains near the 20% target.

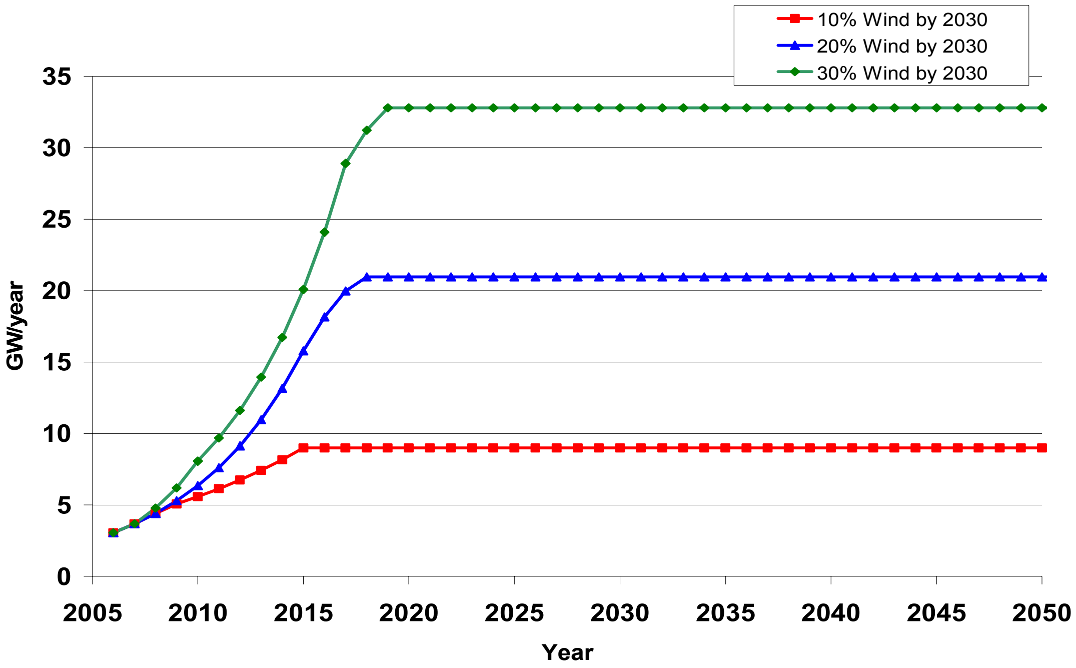


Figure 6. Manufacturing production level required to meet energy supply goals by 2030

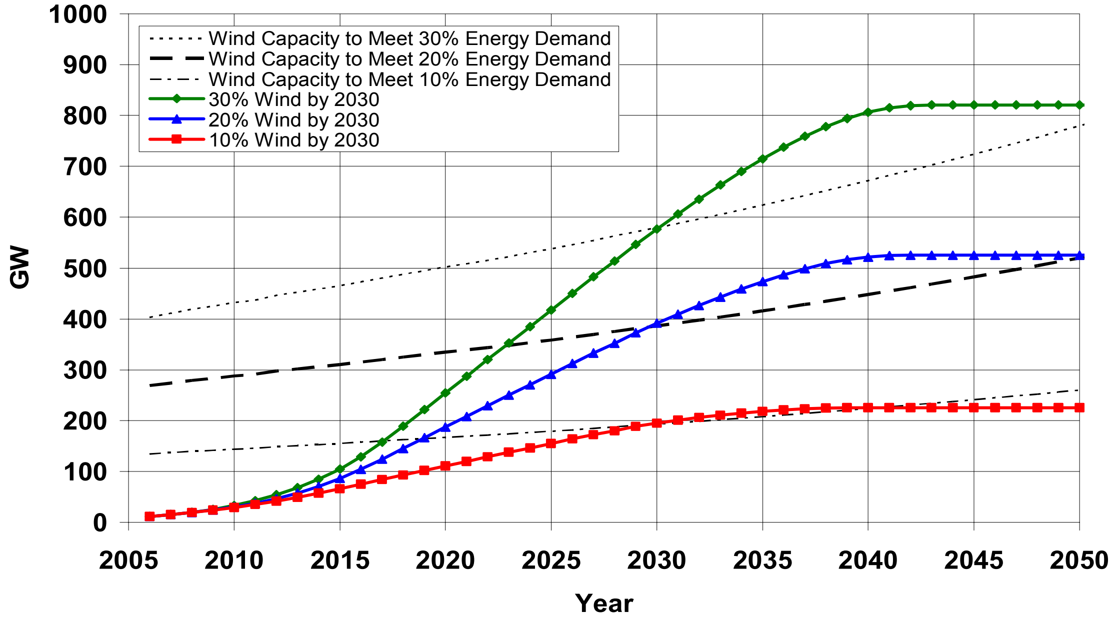


Figure 7. Cumulative wind generation capacity assuming production continues at maximum level after energy generation goals met in 2030

Of the six cases explored with the Sustained Manufacturing Models, three require annual manufacturing capacity increases of 20% over a period of 8 years or less: 10% by 2020, 10% by 2030, and 20% by 2030. The other three cases require annual increases in manufacturing levels of 30% over 3 years (30% by 2030), 50% over 4 years (20% by 2020), and 65% over 3 years (30% by 2020). Although an installed capacity increase of 66% was observed in the U.S. wind industry in 2001, sustaining this level of growth over several years is quite ambitious. Sustained growth rates of 50% are extremely ambitious.

A sustained manufacturing capability of 20 GW/year attained by 2020 would facilitate production of 20% of the nation's projected electricity demand by 2030 and would sustain that level of penetration as an entire generation of wind turbines was retired and replaced. Although this model assumes that all turbines installed in the United States are manufactured in the United States, the reality is that many components will probably be manufactured elsewhere. The large size of blades and towers may be such that U.S. manufacturers could compete economically because transportation costs are lower. The global wind industry is growing, and installation increases are expected in Europe and Asia. This growth continues to put pressure on wind turbine manufacturers to meet demand. Increasing U.S. turbine manufacturing capacity may be required to meet significant U.S. electricity penetration levels in the coming decades.

4.0 WinDS Model Scenarios

The WinDS model was used to run four cases to investigate the effects of variations of the PTC to stimulate rapid near-term wind deployment. The WinDS model accesses wind resource distributed by wind class geographically across the country. In addition to land-based wind resources, offshore resources for the West Coast, Northeast Coast, and Great Lakes regions are available. It models more than 350 regions and includes the capability of transporting electricity from one region to another. Wind turbine technology performance and cost improve over time based on the research and development investment projections of the DOE Wind Program (NREL 2006). Conventional plant costs and performance, along with future fuel prices and energy demands, were obtained from the EIA AEO 2005 (EIA 2005). Unlike the Sustained Manufacturing Model, wind energy capacity deployment is determined by the combination of capacity sources that provide the least cost to the system and are stimulated by policy incentives. In this study, the federal PTC was used to create additional near-term demand for wind energy capacity.

Several caveats are related to the use of WinDS for high-penetration scenarios that should be considered when reviewing these results. One of the major issues with simulating high-penetration cases is that the resulting rapid changes to the mix of electricity generators would probably result in different short-term electricity and fuel costs. WinDS does not include a feedback mechanism that allows changes in electricity and fuel prices to be endogenously modeled. To do that, a complete set of appropriate inputs, including electricity demand and fuel prices, would be necessary (EIA did this for its analysis of the Climate Stewardship Act [EIA 2004]), or additional information about fuel price elasticity and electric demand elasticity would need to be added to the model. Efforts to implement these alternative input sets or elasticities are anticipated in the future.

Another variable that is difficult to model in these scenarios is the impact of global growth in the wind market in parallel to (or even preceding or following) the U.S. market growth. International markets could significantly mitigate or exacerbate the dramatic changes in necessary manufacturing capacity in several of the WinDS cases presented here. We can assume that the international markets would not select the same incentive structure or timeline as the United States. Finally, WinDS uses the AEO 2005 projections for fuel prices and electricity loads, which may or may not be appropriate for high-penetration wind scenarios. We could assume that high-penetration wind scenario policies (PTC extension, etc.) result from some disruption in the energy market (peak oil, radically higher gas and oil prices, public perception of climate change, etc.) that move policy makers in this direction. This disruptive situation would be inconsistent with the AEO 2005 reference case assumptions and could lead to massive wind deployment even without the PTC, depending on the cause of the disruption. However, these variations on PTC structure demonstrate that such policies can stimulate rapid, near-term growth of wind energy in the U.S. electricity market.

The four scenarios modeled with WinDS are described in the following subsections. The resulting wind nameplate capacity is shown in Figure 8; the corresponding percentage of the nation's electricity demand is shown in Figure 9.

4.1 Base Case

The baseline includes only the currently mandated state-level Renewable Portfolio Standards (RPS), state-level PTC and state-level Investment Tax Credit incentives, and the federal PTC, which expires in 2007. An installed wind capacity of 126 GW is achieved by 2030, which is approximately 8.6% of expected total installed capacity. This 8.6% of total installed capacity represents approximately 7.5% of electricity generation in 2030.

4.2 Rampdown PTC to 2020

This case describes a PTC of $0.018/kWh until 2007. It slowly fades to zero by 2020. By 2030, wind energy would have grown to 249 GW installed, approximately 16% of installed electricity capacity. This 249 GW would meet approximately 15% of electricity demand in 2030. The generation percentage peaks in 2020 at 16.7% of demand and then slowly tails off until it levels in 2040.

4.3 Extend PTC to 2010, Rampdown to 2020

This case describes an extension of the current PTC until 2010, after which the PTC amount ramps down linearly to zero in 2021. By 2030, wind energy reaches 293 GW of installed capacity, approximately 18% of predicted installed capacity. This 293 GW capacity would meet approximately 17% of electricity demand in this time frame. This case also peaks in 2020 at a level of 20% of electricity demand, tailing off to 14.5% in 2050.

4.4 Extend PTC to 2020

This case describes a scenario in which the PTC is extended without change until 2020. This case achieves an installed wind capacity of 567 GW by 2020, approximately 30% of predicted installed capacity in that time frame. This installed capacity level then remains relatively flat through 2050. This represents approximately 32% of electricity demand in the 2030 time frame. This model peaks in electricity generation in 2020 at 37.5% because of its rapid ramp rate.

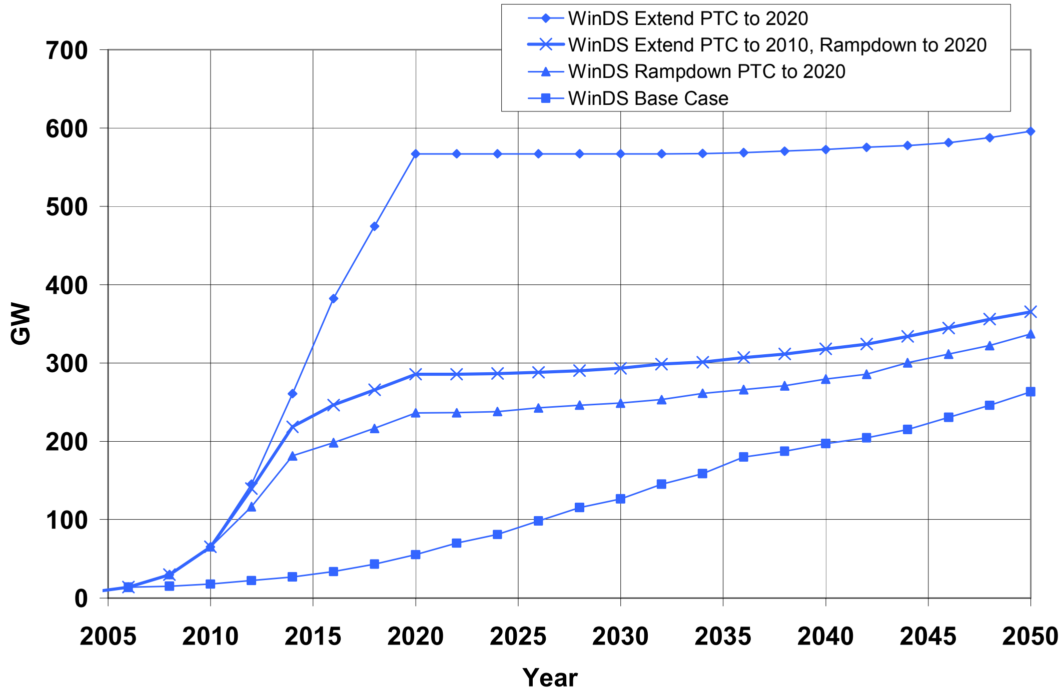


Figure 8. WinDS forecast wind capacity and electrical energy generation percentages under various PTC scenarios

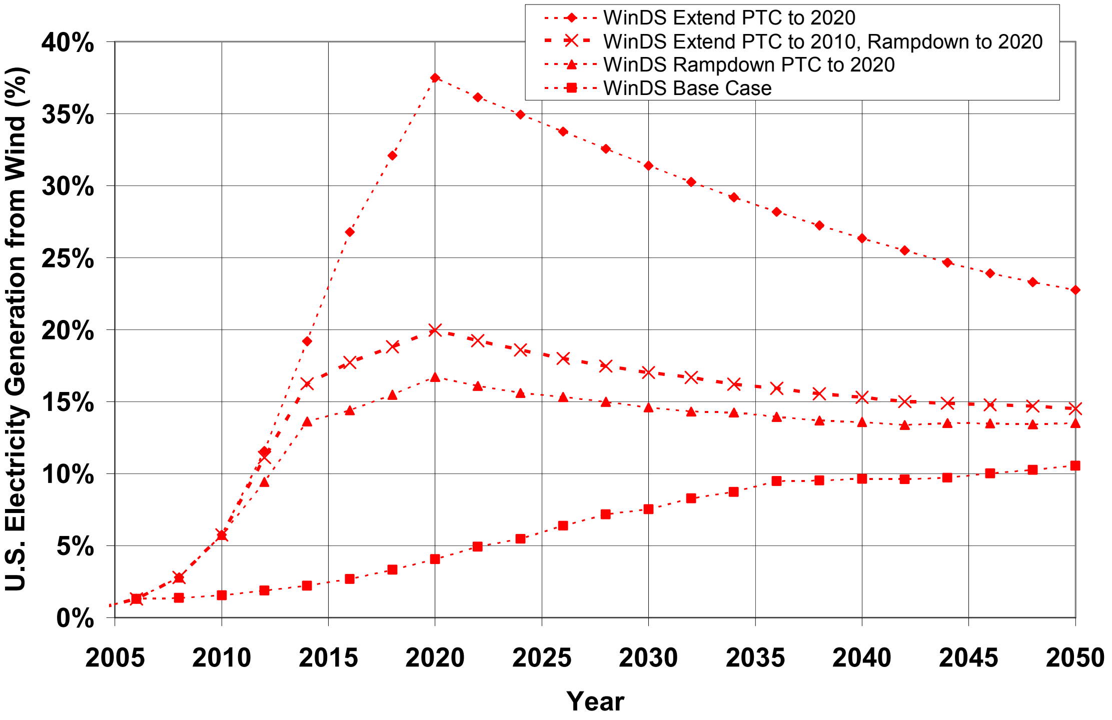


Figure 9. WinDS forecast electrical energy generation percentages from wind under various PTC scenarios

The current WinDS cases do not contain perfect foresight or any other ability to look ahead. This means that the model optimizes each year based on costs during that year. Expansion is primarily market driven, based on conditions during the year in question. The model can contain certain penalty factors to reflect overproduction, but it may not accurately represent foresight. This is most evident in the PTC to 2020 case, in which manufacturing and wind turbine production levels continue unabated until the PTC ends in 2020, and manufacturing falls off drastically as shown in Figure 10. Given the monetary incentive of the PTC, manufacturing of new turbines would likely continue at full production capacity until the PTC ended (the machines installed in the last year of the PTC will still receive the full 10-year benefit of the tax credit), new manufacturing capacity will very likely not be brought on line in the last few years of the PTC because the cost of developing this manufacturing capacity would probably not be recovered.

This curtailing of new manufacturing production is not reflected in WinDS. However, no additional annual manufacturing capacity is added after 2016 in this case and even earlier in the less aggressive PTC cases. Additional approaches are being explored to more accurately model the effects of an expiring tax credit in WinDS. In the scenarios where the PTC ramps down to zero, however, annual manufacturing capacity additions are reduced as the PTC amount declines. When the PTC incentive expires after 2020, the demand for new wind capacity is essentially zero. Repowering turbines that were installed between 1996 and 2005 provides the only new wind capacity between 2021 and 2030. Then demand shifts to repowering turbines that were installed during the period when the PTC incentive was in place. (The Sustained Manufacturing Models seek to reduce the peaks and raise the valley by ramping quickly to a constant level. In reality, repowering will occur over a longer period than at an exact 25-year interval, which raises the valley somewhat).

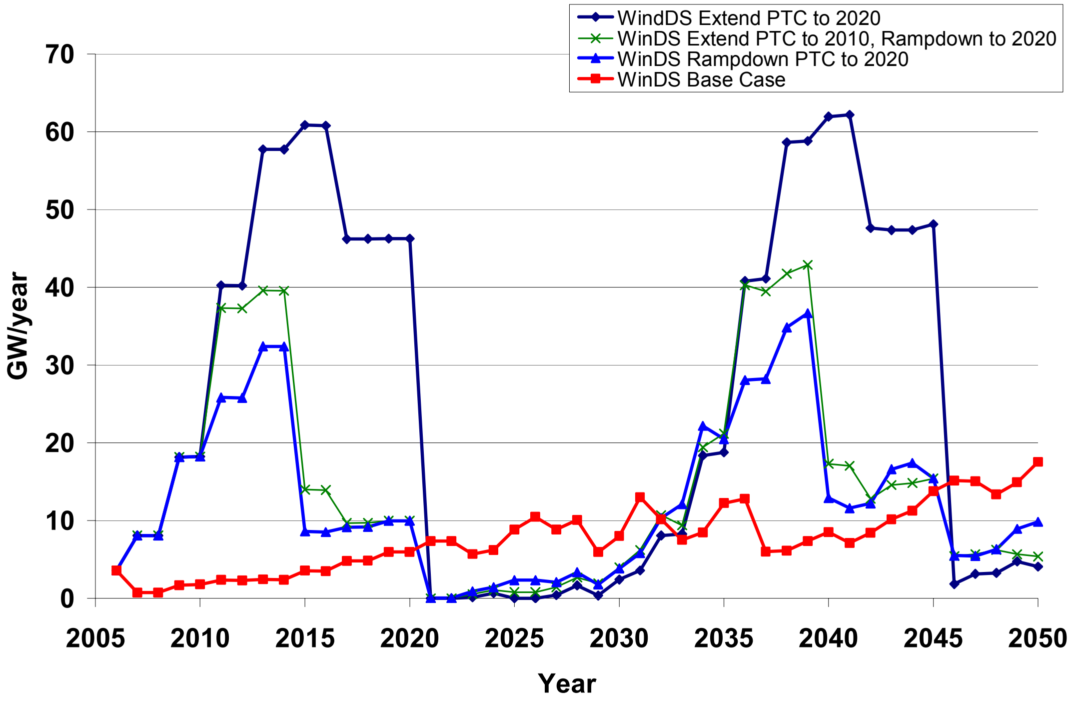


Figure 10. Manufacturing production levels corresponding to WinDS scenarios

The WinDS baseline case projects maximum manufacturing capacity increases of approximately 25% per year, at peak. Based on industry history, these increases appear to be easily sustainable. However, the PTC extension models produce increases of manufacturing capacity of as much as 110% in a given year. This occurs in the PTC extension to 2020 case, but other increases of as much as 60% or more occur in selected years. These levels of manufacturing increase might appear extraordinary, but the nature of wind turbine manufacturing lends itself well to this type of production increase. Wind turbines consist of several large-scale subsystems that can be built in subsidiary facilities. Many new wind assembly facilities are being developed in some of the many older manufacturing plants that dot the country. These facilities can often be easily rehabilitated and can carry significant enterprise zone tax credits with them. Sterzinger and Svcrek (2004) identified many such locations around the country.

Current wind component manufacturing processes are highly labor intensive and in many cases do not require the use of specialized fabrication assembly lines; unlike, for instance, an automobile assembly line that requires many months or years to set up (consisting of specialized handling, welding, treating facilities). Significantly increasing the production of wind turbines requires fabrication of additional blade molds. Once the original plug for the mold is created, additional molds can be fabricated very quickly. A dozen such molds could be developed in a few months, thereby increasing blade fabrication capacity by 10 times or more. People to fabricate the blades can easily be trained, as has been shown in the number of new blade facilities established in the United States over the past few years to meet increasing demand. Other critical components, such as gear boxes, require the production of additional casting molds, which much like blade molds, can be created quickly. Wind energy, because of its distributed nature, already lends itself to the distribution of new assembly facilities over geographically diverse regions. This geographic diversity also aids in increased production by spreading demand to widely distributed industrial regions and not overloading critical manufacturing centers of the upper Midwest and East Coast.

Combined cycle gas turbine (CCGT) and simple cycle gas turbine (SCGT) installations and increases in manufacturing far exceeded the levels described here for wind. Between 1999 and 2000, CCGT and SCGT installations jumped from 3.5 GW to 9 GW installed, an increase of 257%, requiring a requisite increase in manufacturing capacity. Between 2000 and 2002 installations increased by a further 54 GW, almost a 590% increase in production (see Figure 11). CCGTs have many similarities to wind turbines. They are primarily assembled in factory-like assembly facilities from specialized components that can be manufactured by subsidiary facilities. Fully assembled units or subassemblies are then shipped to the installation site. This allows the site to be prepared and foundations to be built in parallel to equipment fabrication and assembly. This closely resembles the model for wind turbine fabrication, assembly, and installation.

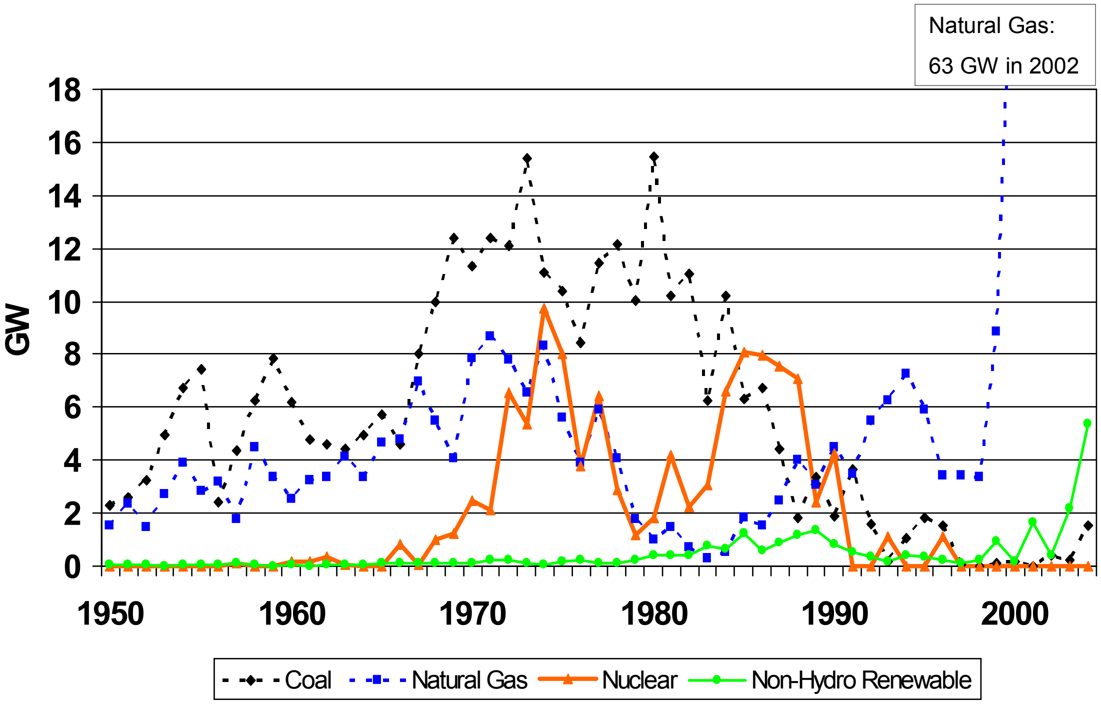


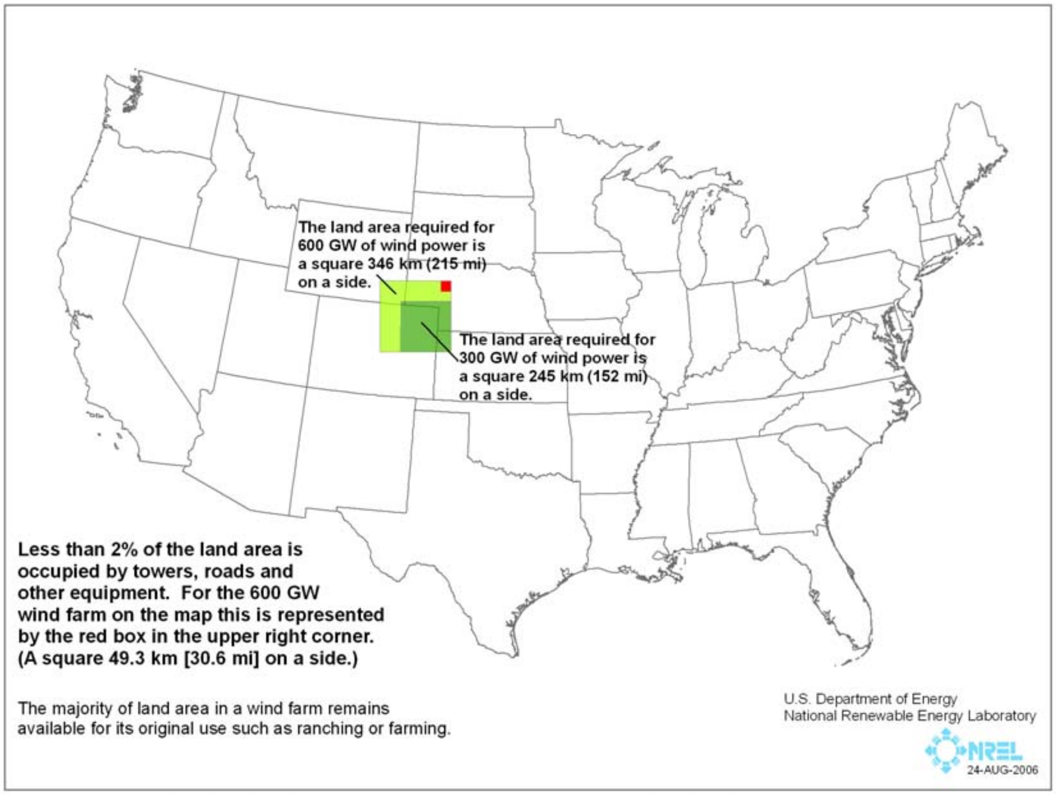
Figure 11. Annual electricity capacity additions from 1960 to 2005 (NREL Strategic Energy Analysis Center from Platts PowerDat database)

5.0 Availability of Critical Resources

5.1 Land

The United States has abundant wind resources (Elliot et al. 1987) that can easily supply significant electricity demand. The land area required for 600 GW of wind capacity is computed based on average turbine spacing of 5 MW/km^2 (Actual turbine spacing density is site specific and varies with terrain). A very small portion of the total land area, approximately 1 acre/MW (according to industry rule of thumb), is occupied by turbine towers, access roads, and other equipment. The rest of the land remains available for farming, ranching, and other uses. As turbine size increases, the land area dedicated to tower foundations increases slightly, but the land area dedicated to access roads is reduced. Estimates of land area required for turbine foundations and access roads for a 50-MW wind farm by Shafer et al. (2001) are reduced by 58% when 5-MW turbines replace 750-kW turbines. There are already regularly spaced roads in much U.S farmland, and new roads specifically built for wind turbine access could be minimized.

A wind capacity of 600 GW would supply nearly 40% of the projected energy demand in 2020; 300 GW would supply nearly 20% of the projected energy demand in 2020 based on the assumptions used to generate Table 1. The land area required to support these levels of wind capacity is a small portion of the contiguous U.S. land area, 1.6% for 600 GW and 0.8% for 300 GW, as shown in Figure 12. The land area dedicated to wind turbine tower and road access is an extremely small portion of this total area, less than 2%. A square of 49.3 km (30.6 mi) on a side would be required for 600 GW of turbines, and a square of 34.8 km (21.6 mi) on a side would support 300 GW of wind turbines. As turbine size increases, these dedicated land area requirements will be reduced.



The land area required for 600 GW of wind power is a square 346 km (215 mi) on a side.

The land area required for 300 GW of wind power is a square 245 km (152 mi) on a side.

Less than 2% of the land area is occupied by towers, roads and other equipment. For the 600 GW wind farm on the map this is represented by the red box in the upper right corner. (A square 49.3 km [30.6 mi] on a side.)

The majority of land area in a wind farm remains available for its original use such as ranching or farming.

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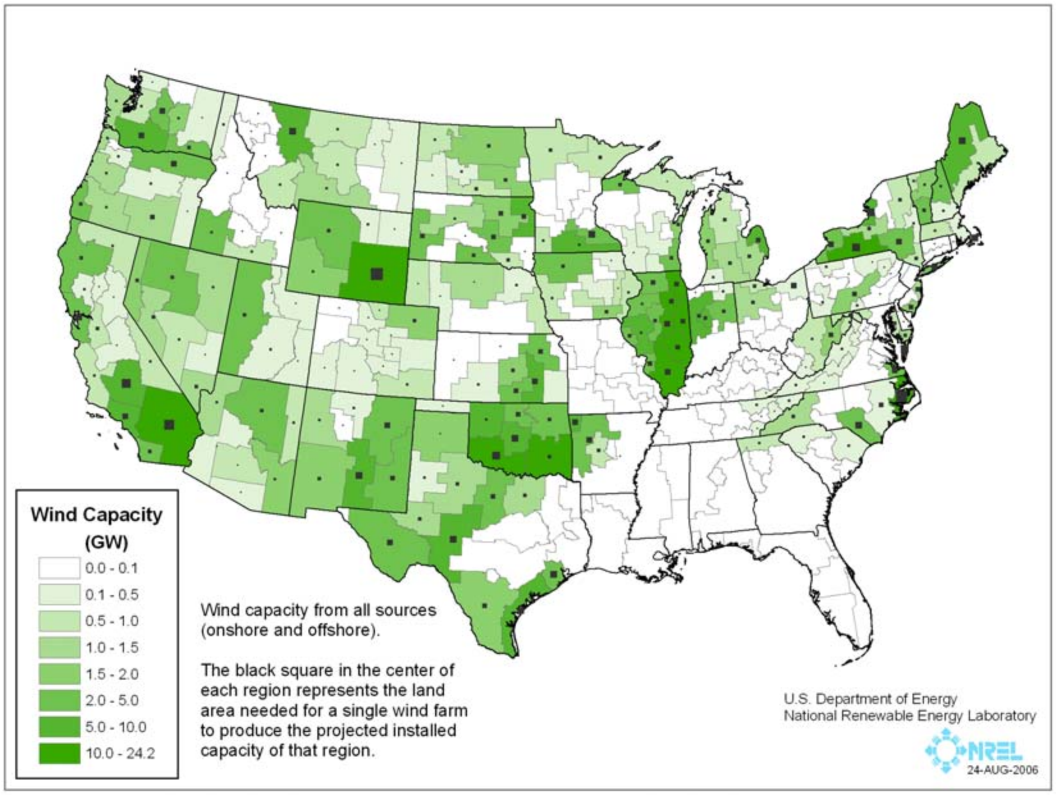
Figure 12. Land area required to support 300–600 GW of wind energy capacity, which represents approximately 20%–40% of projected electricity demand in 2020

The land area required to support high wind electricity generation levels is a small portion of the total U.S. land area. However, the actual locations of wind capacity would be distributed throughout the country. Figure 13 shows each of the regions modeled in WinDS where wind capacity would be installed for the case where the PTC was extended to 2010 and phased out by 2020. This scenario resulted in wind capacity that can generate about 20% of the nation's electricity in 2020. The entire region is colored, although the wind farms associated with the capacity level for a given region would occupy only a small portion of the region represented by the black square. Again, the land area occupied by the turbine towers and access roads would be less than 2% of wind farm land area. Regions with less capacity would require less land area. Wind energy capacity that results in electricity supply of approximately 20% of the nation's demand would be distributed all across the country based on wind resource and transmission considerations.



Wind capacity from all sources (onshore and offshore).

The black square in the center of each region represents the land area needed for a single wind farm to produce the projected installed capacity of that region.

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Figure 13. Wind capacity installed by region for WinDS scenario of extending the PTC to 2010 and ramping down to 2020 as modeled in 2020. The map represents a total installed wind capacity of 284 GW, which corresponds to about 20% of projected electricity demand.

5.2 Steel

Models developed by Laxson and Hand (2006) were used to estimate the amount of steel that would be required per megawatt of wind generation capacity (114 tonnes/MW. Based on the U.S. production of 93.9 million tonnes in 2005 (International Iron and Steel Institute 2005), the manufacturing levels in all of the scenarios presented remain below 8% of U.S. annual production, assuming a 0.5% annual production growth rate from 2005 levels. This is shown in Figure 14 for two Sustained Manufacturing Model cases as well as two WinDS scenarios. In 2005, the United States produced 8% of the worldwide total of 1,129.4 million tonnes, behind

China (30%) and Japan (9%). The steel demands from projected wind energy growth, excluding the case where the PTC is extended to 2020, are an insignificant portion of this total production. Even at 7% of U.S. production associated with the case where the PTC is extended to 2020, this demand doesn't seem impossible to meet. Furthermore, steel would be required for any electricity generation technology installed over the next several decades. Steel is commonly recycled, so replacing turbines after a 25-year lifetime would not require significant additional ore.

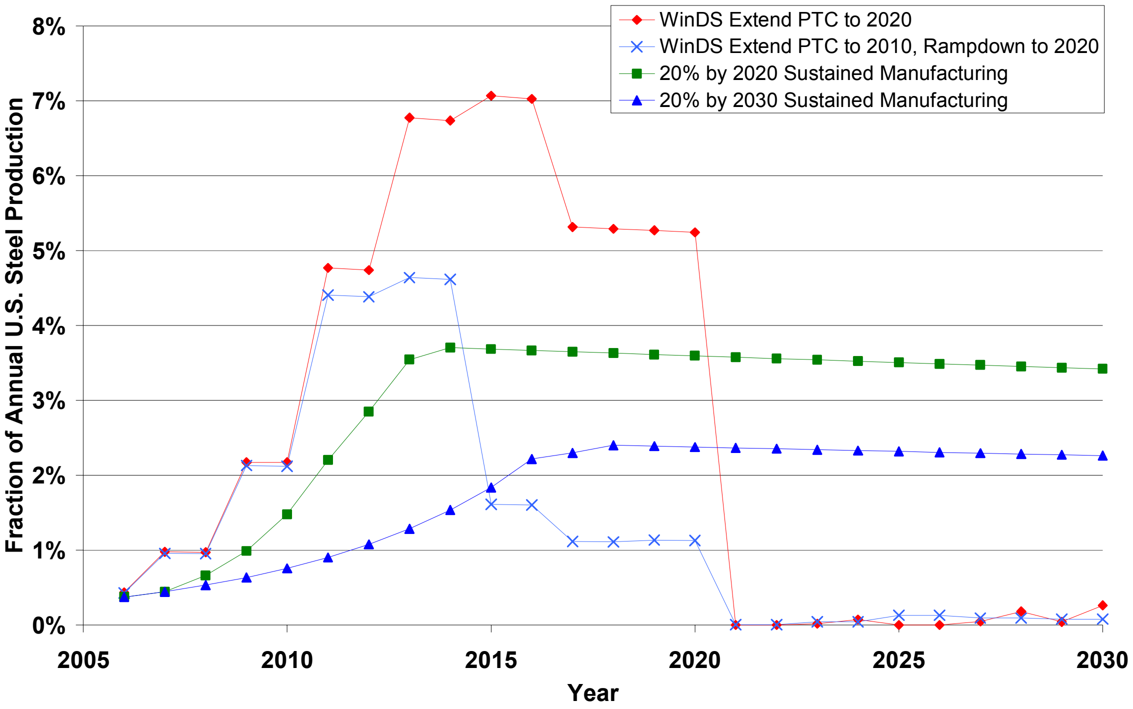

Figure 14. Percentage of U.S. steel production required to meet manufacturing levels associated with selected scenarios. The percent of annual production is based on 2005 U.S. production of 93.9 million tonnes and an assumption of 0.5% annual growth rate in steel production through 2030.

5.3 Fiberglass

Fiberglass blades represent one of the largest components of wind turbines. Estimates indicate that approximately 8.4 tonnes of fiberglass will be required for 1 MW of wind turbine capacity. According to Pittsburgh Plate Glass (personal communication, 2006), annual fiberglass production in 2005 was about 1.36 million tonnes. The most aggressive scenario modeled, extending the PTC to 2020, would require nearly 35% of annual U.S. fiberglass production for a 4-year period (see Figure 15). The more moderate scenarios would still require about 20% of the annual U.S. fiberglass produced. Meeting this type of demand could require additional fiberglass furnaces. Since the primary raw material for fiberglass is sand, there appears to be no shortage of this raw material. However the assembly of fiberglass into blades requires petroleum products such as vinyl resins. The availability and cost of these resins could be expected to fluctuate significantly.

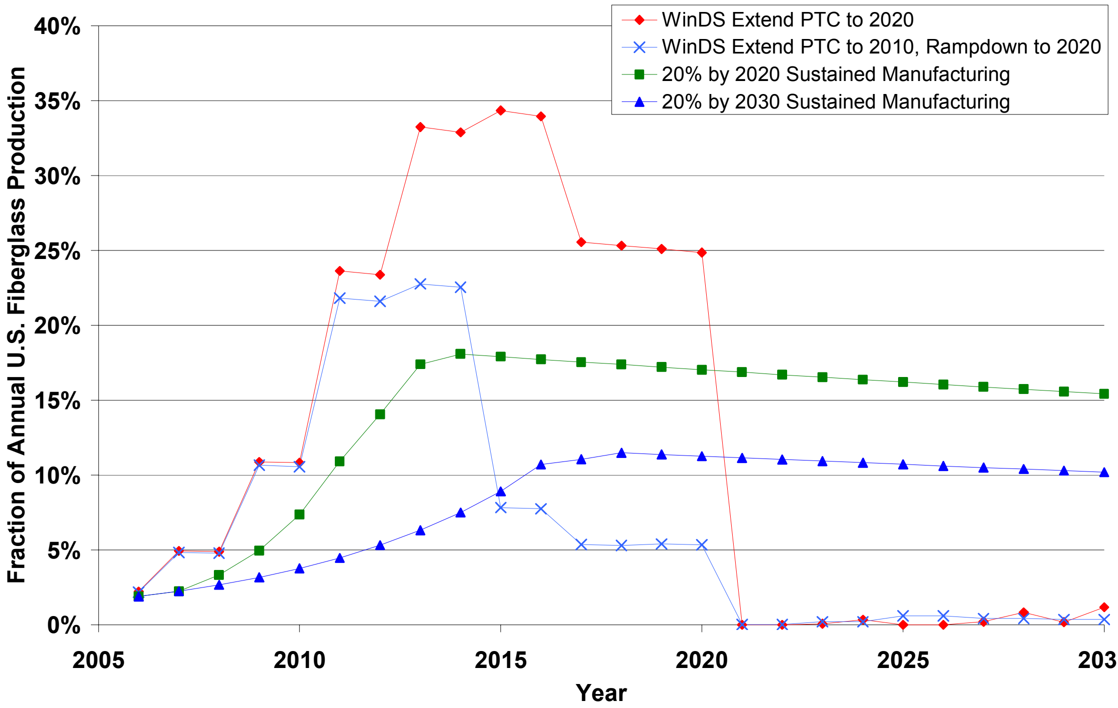

Figure 15. Percentage of U.S. fiberglass production required to meet manufacturing levels associated with selected scenarios. The percentage of annual production is based on 2005 U.S. production of 1.36 million tonnes and an assumption of 1% annual growth rate in fiberglass production through 2030.

5.4 Rare Earth Permanent Magnets

Permanent magnets are becoming economically feasible for wind turbine generators. This technology yields smaller, lighter generators by eliminating copper from the generator rotor. Permanent magnets are manufactured from lanthanides, which were originally termed “rare earth” minerals. The world supply of these minerals is currently believed to be abundant according to Trout (1990) and the U.S. Geological Survey (USGS) (Hedrick 2004).

Although estimates of mineable quantities of permanent magnets do not appear restrictive, manufacturing of the finished magnet products may become a constraint (Trout 2002). The United States did not produce any rare earth materials domestically in 2005. Estimates of global permanent magnet production in 1999 were 13 million tonnes, and the USGS estimates annual growth rates of 28.5% since that time. Because some competing industries expect to increase use of these materials, a conservative growth estimate of 1% for wind turbine usage was used. Figure 16 illustrates the market share of permanent magnets associated with several scenarios. The most aggressive scenario of extending the PTC to 2020 could require more than 50% of the global permanent magnet supply; the more moderate scenarios would use 30%–40% of the global supply. (This assumes that all new wind turbines have converted to the use of rare earth permanent magnets for direct-drive configurations. Most machines at this time still depend on wound rotor technologies.) Significant additions to permanent magnet manufacturing capacity would be required globally to meet the demand for wind turbines and other competing uses. However, assuming 579 GW of capacity and 800 kg/MW of permanent magnet material, more than 463,000 tonnes represents 2.6% of the 17.8 million tonnes of U.S. reserves reported by the USGS in 2005 (USGS). Manufacturing capability must be increased, but there does not appear to be a resource limitation for permanent magnets. As turbines are replaced after a 25-year life, the rare earth magnets can be recycled.

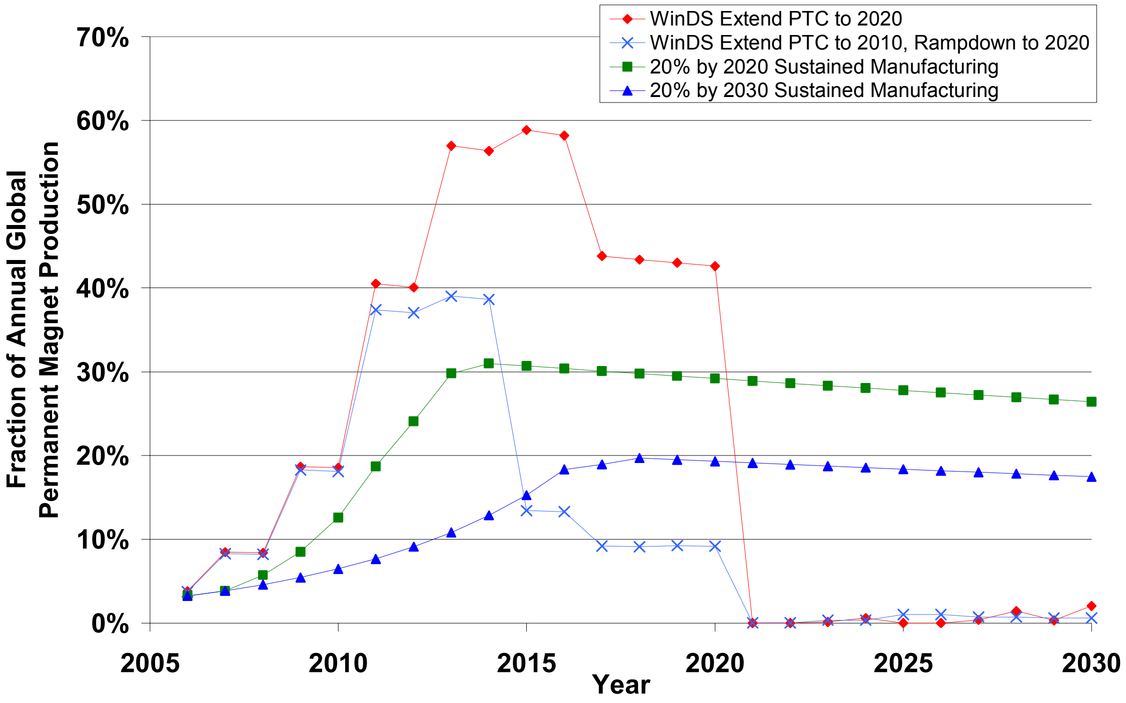

Figure 16. Percentage of global permanent magnet production required to meet manufacturing levels associated with selected scenarios, assuming all turbines have permanent magnet generators. The percentage of annual production is based on 1999 global production of 13 million tonnes escalated 28.5% annually to 75 million tonnes in 2005 according to USGS estimates and an assumption of 1% annual growth rate in permanent magnet production between 2005 and 2030.

5.5 Copper

Copper is used extensively in the electricity industry, and is a component of all generators. It will be a significant component of any electricity generation technology installed in the United States over the coming decades. Wind turbines typically consist of a drive train that includes a steel gearbox and a high-speed induction generator that requires copper windings and steel components. One trend in the industry is toward direct drive generators that eliminate the gearbox. These generators will require more copper than do medium- or high-speed generators. The inclusion of permanent magnets in direct drive generators reduces the amount of copper required.

Based on 2005 U.S. refined copper consumption reported by the USGS (2006) of 2.27 million tonnes, the most aggressive manufacturing scenario where the PTC is extended to 2020 would use less than 4% of the available copper, assuming all turbines include direct drive generators with permanent magnets. The other scenarios would require copper on the order of 1%–2% of U.S. consumption in 2005 with the same drive train assumptions. Copper requirements for drive trains that use high-speed induction generators and steel gearboxes (200 kg/MW) remains less than 1% of 2005 U.S. consumption for all scenarios. Shifting drive train systems to direct drive generators with permanent magnets reduces the amount of high-strength, high-quality steel demanded by eliminating the gearbox. Assuming 1400 kg/MW copper for a direct drive generator with permanent magnets, 579 GW of capacity would require 782,000 tonnes of copper. This represents less than 2.5% of the reported U.S. copper reserves (the part of the reserve base that could be economically extracted or produced) of 35 million tonnes (USGS 2006). Copper is recyclable, so the next generation of turbines could reuse a significant percentage of the copper.

5.6 Labor

Employment estimates related to wind turbine manufacturing, installation, and operation and maintenance (O&M) based on annual installed capacity are shown in Figure 17 for selected scenarios. According to the Renewable Energy Policy Project study of manufacturing capability in the United States (Sterzinger and Svrcek 2004), approximately 4300 full-time equivalent (FTE) positions are created per gigawatt of wind turbine capacity; these positions are not distinguished between permanent and temporary positions. The number of jobs in a given year is directly related to the installed capacity in that year. In the WinDS scenarios, the number of jobs varies significantly with economic fluctuations. The Sustained Manufacturing Cases assume constant production over time after the initial increase. There was no attempt to estimate productivity improvements over time that would decrease the number of jobs per gigawatt.

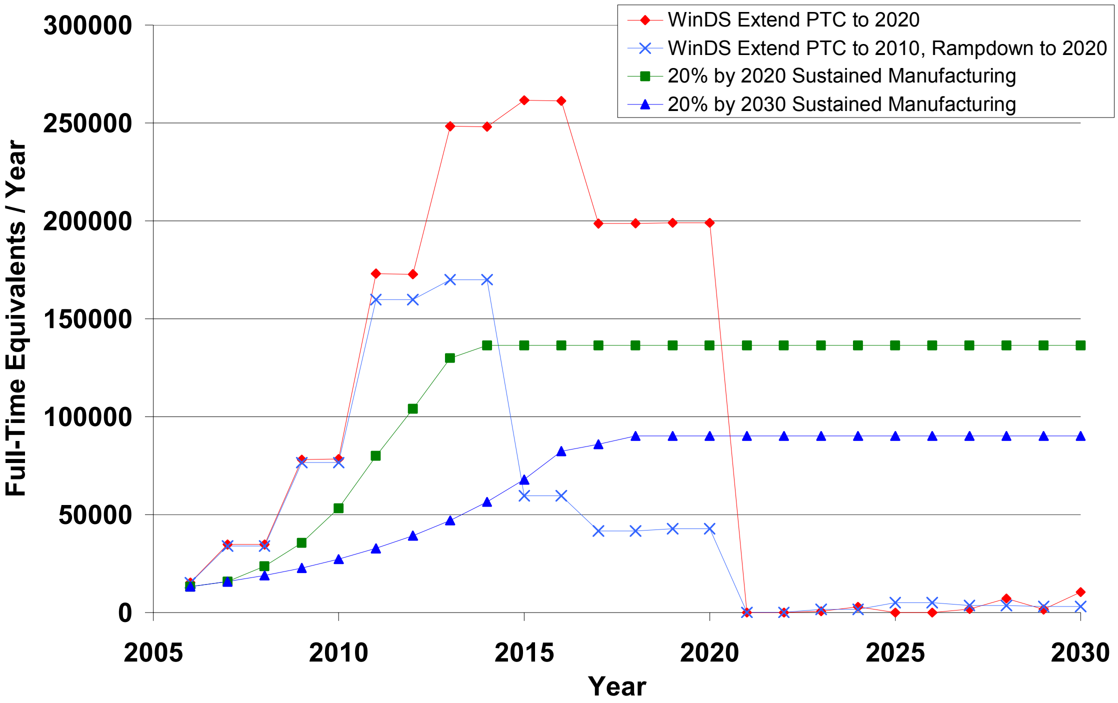

Figure 17. Number of jobs in the wind industry, including manufacturing, installation, and O&M associated with selected scenarios. No attempt was made to estimate increased production efficiency over time, which would reduce the number of FTEs per gigawatt capacity.

6.0 Conclusions

Although aggressive manufacturing growth is required to meet near-term, high wind penetration targets, these rates do not appear to be unachievable. The Sustained Manufacturing Model shows that a manufacturing capacity of 20 GW/year could support a 20% electricity generation level from wind by 2030. Assuming that level of manufacturing is maintained in the United States and that all turbines are installed in the United States, the 20% of electricity generation level would be maintained beyond 2030. This level of manufacturing capacity could be achieved with manufacturing growth rates of 20% per year.

Manufacturing growth rates in excess of 20% per year could occur in response to economic stimulation related to the PTC or achieving wind electricity generation targets of 20% or more by 2020. Although these growth rates are ambitious and excess manufacturing capacity would be built, the modular nature of wind turbines lends itself to this type of manufacturing model. Facilities could easily be constructed and idled based on market conditions. The potential of importing and exporting turbines also mitigates the large fluctuations in demand observed with the WinDS scenarios.

The WinDS economic simulations considered in this study show that an incentive is required to spur high growth rates in the near term. Wind-generated electricity does not significantly penetrate the marketplace at currently projected turbine and fuel costs. A long-term incentive could provide market certainty that encourages the development of domestic wind turbine manufacturing capacity. This study used variations of the federal PTC to stimulate near-term wind energy growth. However, other policies such as a carbon tax or aggressive research and development could be used to make wind more competitive in the marketplace. Also, sustained hydrocarbon price increases could drive growth in wind energy. Such mechanisms for spurring significant growth in wind energy capacity should be studied further.

Achieving high levels of wind penetration in the U.S. electricity market does not appear to be inhibited by the availability of material such as steel and copper. Although additional manufacturing capability of fiberglass and permanent magnets may be required to meet growing wind industry demand, the raw materials do not appear to be limited. The land area required for 300 GW of wind turbines, which would supply about 20% of the nation's projected electricity demand in 2020, would require less than 1% of the contiguous U.S. land area, and less than 2% of that area would be physically occupied by turbines, roads, and other equipment. These wind turbines would be geographically dispersed across the nation.

Numerous barriers to large-scale deployment of wind energy remain, but the materials, land, and capability of the U.S. manufacturing industry to accommodate significant growth do not prohibit wind energy capacities that could provide in excess of 30% of U.S. electric energy generation.

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This study used two different models to analyze a number of alternative scenarios of annual wind power capacity expansion to better understand the impacts of high levels of wind generated electricity production on wind energy manufacturing and installation rates.

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