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SOLUTIONS FOR CONNECTING WIND ENERGY SOURCES TO THE U.S. POWER GRID

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Abstract

The United States is hungry for electricity. Electrical power is the engine for economic growth and is a necessity for a continuously improving standard of living. Policy-makers and technologists are racing to integrate the renewable resource of wind energy into the existing power infrastructure to meet the needs of an ever-increasing population of electricity consumers. However, wind energy has different characteristics than the traditional "dispatchable" (on-demand) power generators. Although opinions vary widely about whether wind energy is a viable alternative to fossil fuel generation, there is no doubt that renewable resources, like wind, must be explored and harnessed in an attempt to support growth while at the same time reducing the environmental impacts of supplying electrical power. The architecture of the U.S. power infrastructure and wind farm layout\turbine architectures are discussed herein. The research for this publication has identified several significant problems for integrating wind energy into the existing power grid as well as potential solutions to the identified problems. No report on wind energy would be complete without a description of the political climate "swirling" around wind power, so this report discusses pros and cons of wind energy and the groups that are involved as supporters or detractors. Conclusions and recommendations are put forth as well.

Keywords: Wind Energy, dispatchable power, Transmission Super Highway, gigawatts, reliability, wind forecasting, wind turbine, wind penetration, fuel cells

1. Introduction

With air quality standards being strengthened, a continued movement to eliminate U.S. dependence on foreign oil, increasing government subsidies for "green energy" providers, heightened public acceptance of renewable energy alternatives, and technological advances in wind generation methods, the problem of interfacing alternative energy generation facilities to the existing and aging U.S. power grid is becoming a subject of critical importance in advancing the availability and reliability of renewable power. Although wind power generation currently only accounts for approximately one percent of the total U.S. generated power, [1]"there are more than 25,000 U.S. turbines in operation, an investment of $15 billion" with the U.S. Department of Energy predicting that [2]"wind power could provide 20 percent of U.S. electricity by 2030 or 304 gigawatts, up from the current 16.8 gigawatts."

The wide open spaces required for consistent wind speeds dictate that most wind farms be located in rural or farming communities where thousands of megawatts (MW) of planned wind generation capabilities can strain [3]"the existing transmission network's ability to transfer power from windy" outlands to large population areas hundreds of miles away. To address transmission shortfalls, some power providers are considering a transmission

[4]"superhighway to take advantage of the huge amount of wind resource in the nation's midsection." While the lack of transmission infrastructure poses problems for wind power generation facilities, other challenges including safety issues, adverse health effects, aesthetic concerns, environmental impacts, and fossil fuel support for alternative options will also be discussed in this report.

1.1.1 Architectural Overview

This section provides a brief overview of architectures for the existing U.S. power infrastructure and for wind farm layout\turbine architectures.

1.1.2 U.S. Power Grid Architecture

The U.S. power distribution grid is currently based on traditional (gas, coal, oil, hydroelectric, and nuclear) power generation facilities. These traditional power generation sources are termed "dispatchable" generators, meaning that they can be, for the most part, started or stopped based on the current or forecasted electrical demand. A map showing a distribution of the largest U.S. power plants by type is shown in Figure 1.

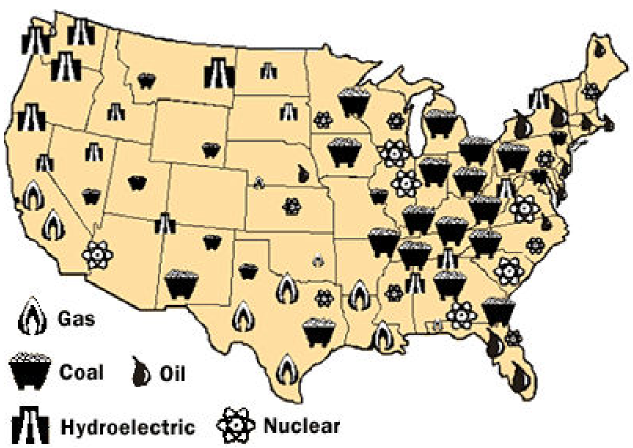

Figure 1

These dispatchable generators produce three phase alternating current (AC) and are connected through transmission substations and transformers that "step-up" power plant voltages to several hundred thousand volts for long-distance "high voltage" transmission. The high voltage is then routed through a substation that has [5]"transformers that step transmission voltages (in the tens or hundreds of thousands of volts range) down to distribution voltages (typically less than 10,000 volts)." Next, a series of substations, transformers, and buses make the power available to commercial and residential end users as shown in Figure 2 below.

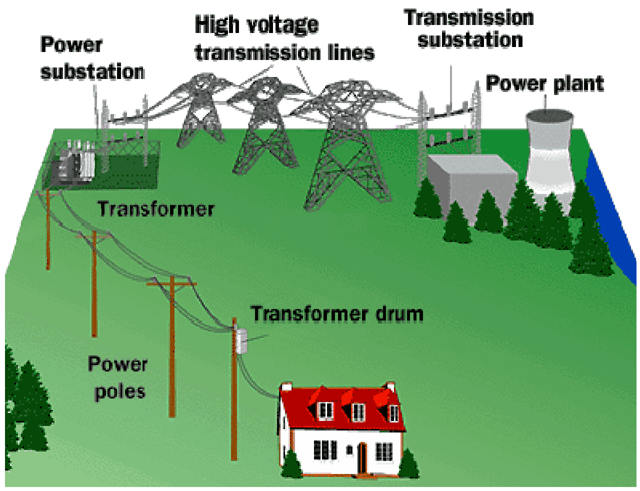

Figure 2

Although Figure 2 shows a nuclear power plant as the power source, any traditional or non-traditional renewable power generation facility can be connected to the transmission substation. Depending on the type of end user, power may only be stepped down to the ten thousand volt range as in the case of industrial power users (not shown in Figure 2).

1.1.3 Wind Energy Basic Design and Interconnection

There are however, specific interconnection and architectural requirements for physically connecting collections of wind turbines (wind farms) to the existing U.S. power grid. The “Wind Power Project” area in Figure 3 shows a simplified representation of the electrical power architecture for a typical wind farm.

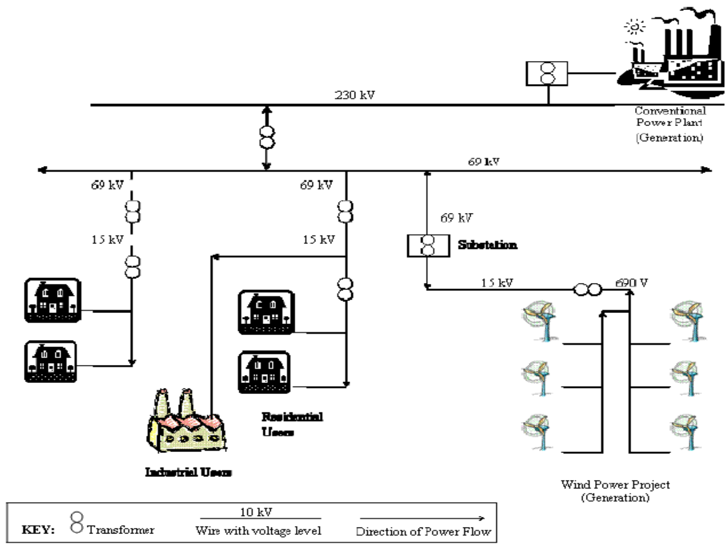

Figure 3

The transformer that is connected directly in line with the wind turbines can consist of one or more [6]"collector substations that consolidate power from the wind turbine generators" and step up voltage for transmission to the interconnect "Substation" where the voltage from the wind derived power is stepped up again and interfaced to the power transmission company. Depending on the distance the wind generated power must travel to the end user, there may be additional transformers that step up voltage to several hundred thousand kV range as shown in the top line voltage of 230 kV in Figure 3. In addition to the vertical buses (feeders) connected to the individual wind turbines in Figure 3, wind farms also can include a management system that [7]"controls the individual turbines to maintain the required voltage at the interconnect substation."

2 Wind Power Problem Identification

2.1 Transmission and Tariff Problems

Transmission problems with respect to wind energy are twofold; lack of transmission facilities to serve remote wind farms and the existing scheduling framework that ensures transmission services and the associated demand are available. Given the wide open spaces required for the installation of multiple two hundred foot tall wind turbines with adequate spacing to eliminate turbulence problems, [8]"good wind sites are often located remotely from electric loads. This means that wind facilities are more dependent upon long-distance transmission and less able to avoid transmission problems than other technologies." The lack of medium and high voltage transmission lines is problematic mostly because of high construction costs but also because current transmission policies were created to manage electricity generated by dispatchable power plants. Accordingly, [9]"many transmission policies assume that generators can control and predict their generation levels and penalize them when they do not" resulting in a competitive advantage for traditional power generation sources when wind power is subjected to the same transmission policies. Since transmission costs can also impact the ability of the wind generation facilities to effectively provide renewable power to the grid, tariff policy and rate structures can affect the ability of wind energy providers to compete with traditional fossil fuel, hydro-electric, and nuclear generation facilities. Again, due to the typical remote location of wind farms, wind energy providers are unusually overburdened by having to pay higher transmission rates to move power to distant load centers in urban areas.

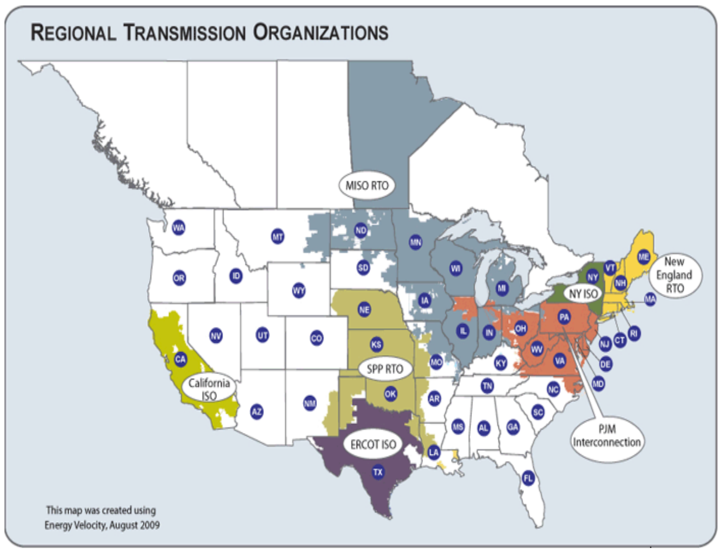

Figure 4

Additionally, because of the lengthy distances between wind energy providers and power consumers, remote renewable energy sources like wind power are forced to use transmission systems owned and managed by multiple entities. The use of multiple transmission networks can make wind farms subject to "pancaking" which [10]"is a function of crossing ownership lines and having to pay multiple access rates that were each developed assuming only a single rate applies. (In other words, the access price for the same transaction using the same pricing policies but assuming a single owner/operator will be substantially lower)." Crossing multiple transmission ownership lines can mean traversing multiple RTOs (Regional Transmission Organizations) as shown in Figure 4. The locations and makeup of RTOs with respect to wind power generation facilities can also cause load balancing challenges for intermittent power sources such as wind generation**.**

2.2 Reliability Problems

Because of the intermittent nature of wind power generation, injecting wind-generated electricity into the U.S. power grid can degrade system reliability. In response to several major power blackouts in the northeastern U.S. over the past few decades, standards have been implemented that state that [11]"it must be shown for all new equipment (transmission lines, generators, substations, and auxiliary equipment) connected at transmission network voltage (facilities operating nominally at 115kV and above, although sometimes voltages below 100 kV are included) that the reliability of the network will not be negatively affected." Until recently, wind power providers have had difficulty regulating voltages of the electricity that was being produced on site by one or more wind turbines which also degrades the overall system reliability of the power grid. A related problem for wind turbines is frequency control. The U.S. electrical power system, like the rest of North America, operates at a frequency of 60 Hertz (Hz). [12]"If electrical load grows faster than power supply, the system frequency will fall below 60 Hz; if the load drops off faster than supply, the frequency will rise above 60 Hz." So, while most traditional dispatchable power generators [13]"have automated governor systems that help maintain system frequency" in response to changes in system loads, many wind energy facilities lack frequency control mechanisms.

2.3 Wind Forecasting Problems

Just as the intermittency of wind power causes reliability challenges for the U.S. power grid, the same variable characteristics of wind prove difficult to forecast when attempting to manage electrical power supply sources and corresponding loads. The main problems for forecasting variations in wind generation scenarios are related to the cost of implementing state of the art forecasting tools, costs for training system operators to use the forecasting tools, barriers to fully integrating wind forecasting applications into existing power system operations, and fostering acceptance of available tools among system operators. Scheduling and accounting for the variability of wind energy can cause significant problems for grid operators who typically receive forecasts from traditional fossil fuel, hydroelectric, or nuclear dispatchable generators. While the dispatchable providers are able to provide accurate day-ahead or several days-ahead forecasts for power to be supplied to the system, wind forecasts can conceivably change hourly. Costs specifically related to forecasting variations in wind that would benefit wind proponents including training, installation, and application expenses would most likely be borne by transmission entities, power companies, and generators. Since [14]"each balancing area is continuously developing plans and schedules for meeting the forecast load while honoring all technical constraints and contractual obligations," there is currently general opposition to introducing yet another complex wind forecasting tool into the current scheduling model. When actual conditions, including load and power generation, deviate from the forecasted conditions, additional costs are incurred by the system, so operators have no incentive to integrate new and unproven forecasting applications. Finally, if system operators see that the wind [15]"forecast information is not presented in a way that is useful to them, they are likely to operate the system in a more conservative manner that will increase cost impacts" on the balancing area as a whole.

2.4 Environmental/Siting Problems

Although the preponderance of literature available on wind power technology is supportive of start-up wind farms and the renewable energy provided by large wind turbines, wind energy has many detractors that cite a variety of negative impacts associated with wind power generation. The vast number of huge wind turbines required for even a modest sized wind farm range from one hundred to two hundred at a minimum. The Horse Hollow Wind Energy Center in central Texas shown in Figure 5 has over (400) General Electric and Siemens wind turbines installed. Several lawsuits have been filed in an attempt to halt installation and/or force the removal of turbines

Figure 5

that consist of [16]"a 200- to 300-foot tower supporting a turbine housing the size of a bus (Figure 6) and three 100- to 150-foot rotor blades sweeping over an acre of air at more than 100 mph. On a GE 1.5-MW tower, the turbine housing, or nacelle, weighs over 56 tons, the blade assembly weighs over 36 tons, and the whole tower assembly totals over 163 tons."

Figure 6

High noise levels and "flicker" caused by the shadows of the huge blade assemblies have also been the source for complaints from residents living and working in close proximity to the mammoth wind generators. [17]"A neighbor of the 20-turbine Meyersdale facility in southwest Pennsylvania found the noise level at his house, about a half mile away, to average 75 dB(A) over a 48-hour period, well above the level that the EPA says prevents sleep." While the movement of the wind turbine blades has been cited as an annoyance, the impact of the giant wind turbines on wildlife has many environmentalists calling for action on the part of wind farms to reduce avian fatalities. For example, [18]"a 2002 study in Spain estimated that 11,200 birds of prey (many of them already endangered), 350,000 bats, and 3,000,000 small birds are killed each year by wind turbines and their power lines." From an aesthetic standpoint, many wind energy detractors simply find the monstrous turbines to be unattractive and a scourge in an otherwise pristine wilderness.

3 Solutions to Wind Power Challenges

3.1 Transmission and Tariff Solutions

Many of the solutions to the lack of transmission capacity put forth by wind energy proponents suggest that someone other than wind power providers (i.e. consumers or traditional power generators) absorb the costs for expanding the current U.S. power infrastructure to serve remote wind farm locations. For instance, [19]"AWEA strongly believes that it makes sense that end-use customers should be allocated 100% of the embedded costs of the transmission system" which could result in a significant increase in residential and commercial power bills and possibly turning public opinion against renewable power sources like wind energy. Construction of a transmission "super highway" that would provide a backbone for transmission services to the remote areas where wind farms are typically built is one proposed solution for connecting large wind generation facilities to the U.S. power grid. However, some cost savings in the grid system must be identified so that consumers are not forced to bear the entire price increase in power that would most certainly be passed onto to power customers if energy companies alone are responsible for paying for hundreds of miles of new transmission facilities. Therefore, tax breaks for the construction of transmission components should be offered as an incentive to raise private capital to fund the transmission facilities that wind energy will require. Some subsidies for wind generated power should remain in place for a strictly limited timeframe to enable wind energy providers to overcome the barriers of entry into a firmly established energy market that is unfamiliar with renewable sources and in some cases, unwilling to integrate wind power into the existing system. One way to generate cost savings from the existing grid system is the use of "smart" power meters that enable consumers to voluntarily reduce their energy usage during peak load times which in turn can reduce the requirement for new generation and transmission facilities to serve ever increasing customer loads. Another cost saving vehicle would be the implementation of fuel cells to capture the potential of wind energy during periods of low power demand. Huge liquid fuel cells could be constructed near wind farms that would make power available to under-served rural communities that are not currently served by the existing grid infrastructure.

3.2 Reliability Solutions

As mentioned in the Problem Statement section above, blackout problems in populous U.S. urban centers led to the implementation of reliability standards for load serving entities and transmission organizations. In addition to reliability targets that were created by the North American Electric Reliability Council (NERC), Regional Reliability Organizations (RROs) provide a localized governing body to insure standards are upheld. An RRO map is shown in Figure 7.

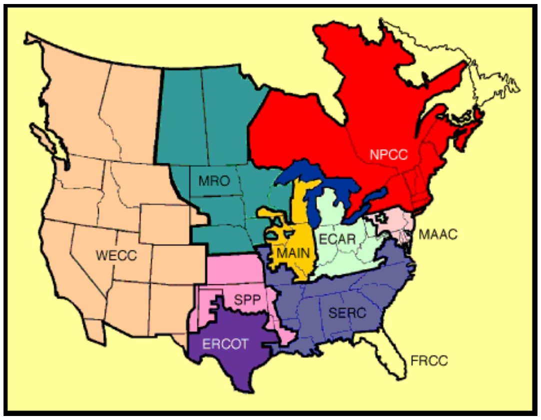

Figure 7

RROs are responsible for conducting "steady-state" studies which include RRO power flow models and "stability analyses" that are intended to [20]"assess the effects of the new facility (wind) on the ability of the power system to recover from major disturbances without cascading outage of additional equipment." Wind turbine manufacturers GE Energy and Siemens Power Technologies both market computer applications [21]"capable of performing flow calculations and dynamic simulation of very large power systems" that are intended to address the reliability challenges associated with the intermittent characteristics of wind energy. From the wind turbine design perspective, several wind turbine generator options have been proposed to provide more consistent voltage levels at the required frequency (60 Hz) to the power grid. Constant voltage levels become increasingly important because of the potential long distances that power must travel from remote areas to interconnection points. The incorporation of Doubly Fed Induction Generators (DFIGs) in wind turbine designs by [22]"half of the world's leading wind turbine manufacturers" has reduced power and frequency variances attributed to wind energy generation. DFIGs (Figure 8) enable the use of variable speed wind turbines that [23]"reduce mechanical stresses: gusts of wind can be absorbed, dynamically compensate for torque and power pulsations caused by back pressure of the tower" in addition to controlling power levels. More sophisticated DFIGs include electronics that can control the pitch angle of the wind turbine rotor blades to further reduce the effects of wind speed variability.

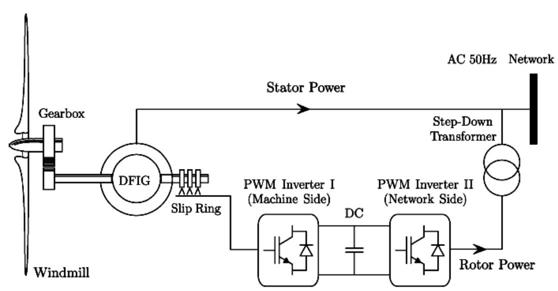

Figure 8

3.3 Wind Forecasting Solutions

Several factors have contributed to the heightened accuracy and utilization of wind forecasting tools. **Enhanced Technical Tools:** Wind forecasting software applications that incorporate simulation and modeling have vastly improved as wind energy penetration has increased. Federal and State renewable energy targets and mandates are encouraging system operators to use [24]"physics-based forecasting models, real-time wind and energy data from wind plants, and computational learning systems such as artificial nets or support vector machines to provide forecasts of wind energy delivery that are significantly better than simplistic forecasts based on climatology." Whereas standard weather forecasts typically cover very large land areas, researchers [25]"have developed higher-resolution models that simulate airflow over smaller areas. Improved grid resolution would likewise improve the accuracy of wind-energy forecasting models." Moving from image (a) to image (d) in Figure 9 shows how smaller grid resolutions can provide more relevant wind data to forecasters by magnifying specific geographic regions.

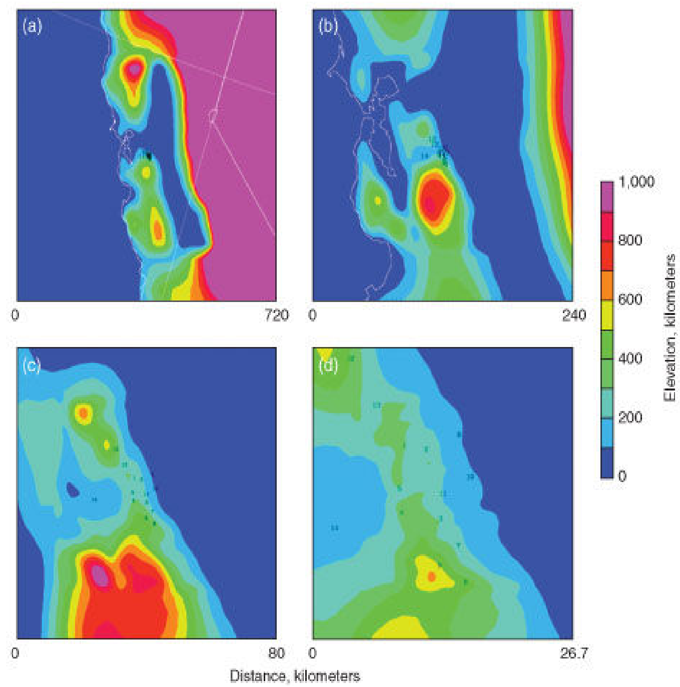

Figure 9

Increased Wind Energy Penetration: As more wind farms are being brought on line, more operators are recognizing the need to make wind forecasting a part of their balancing and scheduling process. Furthermore, the use of forecasting tools becomes acutely important when attempting to determine the potential impact of high wind periods on the power system and load balancing. **Energy Management System Upgrades:** An indirect impact of increased wind energy penetration is that Energy Management Systems (EMSs) are beginning to incorporate sophisticated wind forecasting tools within the traditional EMS planning and scheduling capabilities. At a lower level, the Dispatcher Training Simulator (DTS), which is the training environment that simulates a production EMS, should include [26]"areas for integrating wind forecasting information more tightly into power systems operations for both analysis and operator training scenarios."

3.4 Environmental/Siting Solutions

The inherently annoying aspects associated with wind power have been given a label; "wind turbine syndrome." And while scientists are not in agreement whether wind turbine syndrome actually exists, turbine manufacturers are attempting to address noise issues related to the constant spinning of the 100 foot plus long turbine rotor blades. [27]"To solve this sound issue, new wind-power technology employs sound-dampening systems. Engineers are hoping that these newer systems, which can block or cancel out multiple sound frequencies, will reduce any sound-related problems associated with wind farm communities." One simple solution for mitigating the effects of turbine rotor noise is increasing the distance between residential development and the wind farm locations to create a buffer zone. "Some people say that the distance should be least 1.2 miles (2 kilometers) while others suggest at least 2 miles (3.2 kilometers). Some wind farms are currently located as close as a half mile (0.8 kilometers) from residential areas" which common sense would dictate as being too close. Scientists are also working to minimize the negative impacts that wind farms pose to wildlife and the environment. Specifically, researchers are using geographical information system (GIS) technology to determine bird activity in areas with large wind farm penetration. [28]"The GIS analysis provided details such as flight patterns and timing, terrain gradients, and wind direction. The overall visual representation showed where turbines are located relative to bird sightings" as show in Figure 10.

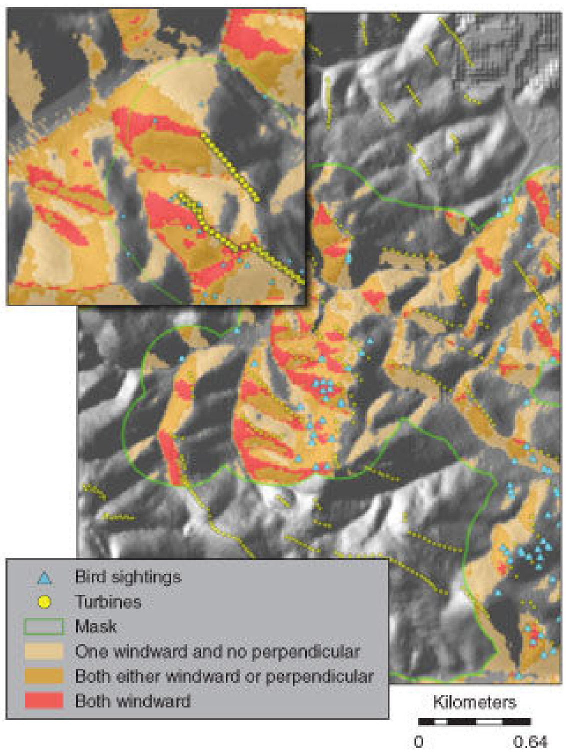

Figure 10

Data from similar studies in wind farm dense areas will lead to more avian-friendly wind turbine placement and fewer bird deaths.

4 Solution Summary and Financial Discussion

4.1 Solution Summary

The solutions put forth in this paper highlight some of the most visible and polarizing problems facing wind energy proponents and their industry partners. The problem areas for integrating wind energy into the existing grid infrastructure represent differing priorities for different interest groups. While a resolution of the perceived inequities in the existing transmission and tariff structure is of grave importance to wind energy providers who are attempting to compete with entrenched fossil, hydroelectric, and nuclear providers, the reliability organizations (RROs) and power system control personnel who must satisfy electrical demands on a hourly and daily basis are concerned with ensuring the reliability of the wind power newcomers. As expected, environmentalists and consumer groups favor the solutions that minimize impacts on wilderness areas, animal populations, and human residents who live in close proximity to large wind farm installations. And even though wind energy proponents express concern for environmental impacts, they continue to focus more on the integration of state of the art wind forecasting tools in power system control rooms. Based on projected growth rates for U.S. consumer demand for electrical power over the next few decades, the expansion of transmission capabilities is a high level solution that all parties can support. Whether future power demand is satisfied by traditional providers or by wind providers, a transmission expansion plan to accommodate both fossil fuel generators and wind-based generation could be privately funded, subject to favorable tax treatment by federal and state governments, and supported by cost savings at the grid level.

4.2 Financial Discussion

Depending on the source, a scenario that enables the U.S. to generate 20% of all power requirements from wind energy by the year 2030 will either cost tens of billions of dollars or over three hundred billion dollars. Due to the divergence of opinion regarding the actual costs associated with significant wind energy penetration into the existing U.S. power grid, this section contains only a very high level financial discussion. By design, it appears that those with a vested interest in the success or failure of wind energy are not discussing the direct costs of installing transmission facilities and the thousands of wind turbines required for the 20% by 2030 scenario. What is missing from wind proponent's analyses, is the number of new wind turbines required to generate more than [29]"300 gigawatts (GW) by 2030." However, the wind power detractors point out that DOE plans [30]"based on the wind industry's sales brochures, as well as on a claim of electricity use that is only three-quarters of the actual use in 2002, would require ONLY 142,060 1.5-MW towers." With estimated costs per 1.5 MW wind turbine in the $2 million range based on a recent GE Energy contract [31]"of more than $350 million to supply 167 of its 1.5-megawatt wind turbines" to a large wind U.S. project in 2007, the turbine capital costs alone for a 20% wind scenario by 2030 would easily exceed $250 billion. In a DOE study, wind proponents, estimated costs for turbines, towers, foundations, installation, profit, and interconnection fees at "$1,775 per kilowatt (kW) in 2007, which reduces to $1,650/kW in 2006" which translates to roughly $2.5[32] million for a 1.5 MW wind turbine. Although a case can be made that the cost per MW for wind turbines will decrease over time and a break-even cost point exists for wind versus traditional generation because of the long-term cost of fossil fuels (no fuel cost for wind), traditional power plants with costs inflated as high $1 billion compare favorably to wind because the Net Present Value (NPV) of the $250 billion capital cost for the wind option is still an extraordinarily large amount. And while "the U.S. Energy Information Administration (EIA) estimates that U.S. electricity demand will grow by 39% from 2005 to 2030" wind proponents contend that vastly higher cost wind energy solutions will need to replace the more economically feasible fossil-fired generators to meet the increased forecasted demand. It should be noted that the previously mentioned 142,060 1.5-MW turbines would provide only about 213 GW of the 300 GW required for a 20% wind option by 2030. Therefore, the required number of additional 1.5 MW turbines could well exceed 200,000. To maintain the proper perspective, the monumental costs for wind farm construction and installation do not include the several tens of billions of dollars of new transmission construction costs associated with a 20% wind scenario by 2030 option. Transmission construction cost estimations vary widely and are beyond the scope of this paper.

5 Conclusion and Recommendations

Even though engineers, power company technologists, and wind energy advocates have done much to address the many shortfalls that pose barriers to integrating wind power into the existing U.S. power grid, there are significant challenges that remain and unresolved questions for the future of wind power in the U.S. Wind proponents and engineers offer several solutions to outstanding problems with wind energy, but no source has addressed the sheer quantity of turbines needed and the associated cost to get to a 20% wind scenario by 2030. In addition to the high capital costs for wind farm construction, many wind power detractors point out that wind power penetration will do little to reduce the use of traditional fossil fuel power generators. According to one leading wind opposition group, [33]"If wind towers do not reduce conventional power use, then their manufacture, transport, and construction only increases the use of dirty energy. The presence of "free and green" wind power may even give people license to use more energy." On the other hand, wind power generation does appear to be an excellent option for under-served rural areas that lack transmission facilities, but those same rural communities would still require some means of dispatchable complementary power generation for low (and very high) wind scenarios. Or alternatively, the development and implementation of very large fuel cells for windy rural communities in addition to back-up dispatchable fossil fuel generators may be an excellent fit for wind turbine use. Another related option for wind energy is to use power from wind turbines that is created during periods of low demand (overnight) to lower U.S. vehicle CO_2 emissions. Because of the intermittent character of wind energy, many researchers believe that wind generation is better suited to provide power for the creation of clean burning fuels such as hydrogen for passenger vehicles.

The short term solution for satisfying increasing U.S. power demand, as discussed in Section 5.1 of this paper, is expanding power grid transmission capacity in a manner that will benefit consumers while at the same time attempting to integrate renewable options like wind power into any long term transmission planning. The goal of clean renewable energy should continue to be pursued and encouraged through continued tax incentives and limited government subsidies, but the 20% wind penetration by 2030 that [34]"would require U.S. wind power capacity to grow from the 11.6 GW in 2006 to more than 300 GW over the next 23 years" is an option that is currently too expensive. Wind proponents are correct in forecasting continued increases in fossil fuels for traditional power plants, but the break even cost projections for significant for wind power penetration versus fossil fuel options appears to be decades away with current costs of over $2 million for each 1.5 MW wind turbine.

Based on the current price tags of several high profile wind energy projects, capital costs for wind farms are far too high and must come down before wind energy can achieve high penetration rates. For wind power to become a more substantial percentage of the U.S. power generation mix, vastly improved efficiency for wind turbines and lower cost per MW is imperative. A huge investment in wind infrastructure and wind-related transmission expansion to fund an unproven source of renewable energy would most likely be shouldered almost entirely by the consumer and the taxpayer. Alternatively, smart grid technologies can be implemented to finance transmission infrastructure, tax incentives offered to encourage private investment, and lower cost cleaner burning fossil fuel facilities can be expanded to accommodate increases in the demand for power over the next two decades. Because of the large critical mass of turbines required to achieve the DOE 20% of electrical power by 2030, wind turbines may be better suited as a power source for charging fuel cells or creating clean burning fuels in the short term. As wind energy efficiencies mature over the long term and wind farm costs decline, wind power generation will be well positioned for rapid expansion if fossil fuel prices should rise dramatically.

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