FEASIBILITY ANALYSIS OF COORDINATED OFFSHORE WIND PROJECT DEVELOPMENT IN THE U.S.

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B.S., Earth and Ocean Sciences
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Durham, North Carolina (2006)

Submitted to the Department of Urban Studies and Planning in partial fulfillment of the requirements for the degree of

Master in City Planning

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2008

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ABSTRACT

Wind energy is one of the cleanest and most available resources in the world, and advancements in wind technology are making it more cost effective. Though wind power is rapidly developing in many regions, its variable nature creates obstacles in integrating significant amounts of wind power to the electric grid. One potential solution for reducing the fluctuating nature of wind power is to site wind projects in regions of complementing wind regimes to reduce variability.

This thesis explores the feasibility of creating a coordinated network of offshore wind projects through examining its technological requirements, economic viability, and the policy and planning issues of building such a network in the U.S. Wind speed data for sites along the east coast of the U.S. are used to analyze the nature of offshore wind patterns and the benefits of interconnecting multiple wind projects. The main questions are: 1) Is an offshore wind network technologically feasible? 2) What are the costs and benefits of creating an offshore network with transmission lines? 3) What are potential ways to plan, permit, and develop such a network?

An overview of research on existing turbine technology, turbine foundation technology, and transmission technology show that it is technically possible to build a network of offshore wind projects. An analysis of the costs and benefits of physical interconnection show that the cost savings from reduced variability pale in comparison to interconnection costs. It is more cost effective to coordinate the siting of all projects within the network, by connect the projects directly to the onshore grid as opposed to creating a separate, offshore grid for wind projects. The current planning process for offshore wind development permits projects on a site-by-site basis, so developing an entire network of sites with the goal of reducing variability would require an extensive stakeholder process where all relevant parties agree on a set of sites. A coordinated network could also be developed over time by incorporating variability as a priority in the permitting process.

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ACKNOWLEDGEMENTS

I have been fortunate during this thesis-writing process to have help from a lot of people, some whom I know well, others whom I have still never met.

I definitely underestimated how much trouble I would have addressing this particular thesis topic, and I am very thankful for the patience and encouragement of my advisor, Jonathan Raab. Thank you for agreeing to advise me and for putting up with my many extra draft chapters, long (and sometimes frantic) emails, and propensity for throwing in the kitchen sink.

I am thankful for the help and support of my thesis reader, Greg Watson, who managed to find time out of his ridiculously busy schedule to tell me about the Supergrid and give me advice. Your enthusiasm for offshore wind is unparalleled.

I have received the generous advice and help of many others, without whom I would have been completely lost. Rich Gross gave me a crash course on transmission as well as invaluable resources. Bob Grace and Jason Gifford at Sustainable Energy Advantage shared their advice, concern, and even threw in a financial model. Christina Archer at Stanford University shared her wind data with me, without which I could not have done any of my analyses. Scott Kennedy at MIT explained the basics of wind integration and even sent me his PhD Thesis. Professor Judy Layzer talked me through my initial panic that nothing was close to being cost effective, and Professor Larry Susskind's enthusiasm for the project idea gave me great motivation to continue with it even when I didn't have a clue how to proceed. I also learned a great deal from my conversations with Mike Hogan at MIT, Willet Kempton at the University of Deleware, Peter Raftery of Airtricity, Jess Totten at the Texas Public Utilities Commission, and Walter Cruickshank at the Minerals Management Service. Thank you for being so generous with your time and knowledge.

Finally, I am greatly indebted to many of my friends and classmates who listened patiently while I rambled on about supergrids and transmission lines and gave me good advice and encouragement whenever I needed it.

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INTRODUCTION

Wind energy is one of the cleanest and most ubiquitous resources in the world, which humans have used for thousands of years to propel ships, pump water, and grind grain. Though wind is everywhere, harnessing that wind for electricity requires certain thresholds of wind speeds, geographic and geologic locations suitable for building wind turbines, and the means to move that electricity to where it is needed. This thesis will examine the benefits and obstacles to creating a coordinated network of offshore wind projects as a way to facilitate the growth of wind energy in the U.S.

Offshore Wind Energy Resource

Offshore wind potential is considered to be higher than on-shore wind because offshore winds are stronger and more consistent. A global study of wind patterns found that offshore wind speeds averaged 90% higher than on-shore wind speeds (Archer and Jacobson 2005). Studies done by the National Renewable Energy Laboratory (NREL) have found that the U.S. has 907 Gigawatts (GW) of offshore wind potential between 5 and 50 nautical miles (nm) offshore, which is almost equal to the current installed electrical capacity of the U.S. of 1,067 GW (Musial and Butterfield 2004). However, the majority of those 907 GW will be difficult and costly to harness.

The most cost-effective areas to develop offshore wind are locations both close to shore and in shallow water. Locations within 20 nm of the coastline could use conventional transmission technology, and shallow areas with a depth of less than 30 m could utilize conventional foundation technology. In total, the U.S. has an estimated offshore wind resource of 60 GW within 20 nm of the coastline in shallow water, which could provide 5.6% of the total current installed electrical capacity (Musial and Butterfield 2004). These 60 GW could be harnessed using existing turbine and foundation technology.

If deepwater foundation technology and longer transmission cabling were available and economically viable, the U.S. could harness an additional 141 GW of estimated offshore wind resource within 20 nm of the coastline, providing 19% of the total current installed electrical capacity for the U.S (Musial and Butterfield 2004). Improved transmission systems enabling wind farms to be located beyond 20 nm of the coastline would further increase the offshore wind resource estimate by 38 GW in shallow water, and 668 GW in deepwater. In total, all potential offshore wind resources add up to 907 GW, which is 95% of the total electrical capacity of the U.S (EIA 2008).

These estimates show that wind energy has the potential to become a significant energy resource for the U.S., above and beyond its current level of supplying less than 1% of U.S. energy consumption. However, fully realizing this resource potential would require developing and implementing new technology and refining current policies regarding the wind siting and permitting process.

Clean, Renewable Energy

Land-based wind energy has been harnessed for decades at an industrial scale and is a proven technology. Wind is one of the renewable energy technologies that rely on a free and naturally abundant fuel source. The majority of its costs are capital costs, which are not subject to fluctuating generation costs linked to fuel shortages. Wind energy is also clean energy because wind turbines produce no pollution while operating. Though the manufacturing and installation of the turbines themselves do result in emissions, an offshore wind turbine generally takes 3 months of generating zero-emission energy to offset the greenhouse gases emitted in manufacturing the turbine. Since wind turbines usually have an operational lifetime of around 20 years, a wind turbine generates a significant amount of net-emissions-free energy in its lifetime. For example, a 3.6 Megawatt (MW) turbine can produce up to 622,944 Megawatt-hours (MWh) of net-emissions-free energy in its lifetime, which is the equivalent of 76.5 tons of coal, or 281 tons of CO_2 emissions. A 420 MW wind power plant, over its lifetime, can generate the same amount of electricity as 9000 tons of coal, or 33 million tons of CO_2 emissions (Tester et al 2005). And unlike coal-powered generators, 90%-100% of all materials from a wind turbine can be reused (Krohn 1997).

Obstacles to Wind Power Development

Though wind power is a promising renewable energy resource, it also faces many challenges and problems. One key obstacle that limits wind power from becoming a more significant energy resource is the issue of fluctuating wind speeds in any given area. Though wind is a clean and free fuel, it is not constant and entirely predictable. Because of wind's variability issues, wind is generally capped at 20% of any region's energy supply, and few regions have developed close to that amount of wind power. Integrating large amounts of wind power requires maintaining spinning reserves, power plants that can be quickly turned on to generate power when wind resources are low. Building and maintaining these generators to support large-scale wind integration is costly and creates redundancy in generation resources.

In addition to variability issues, wind power development also entails a number of siting and public acceptance challenges ranging from location of resources to visual impacts.

- Resource Location: Many areas that are optimal for wind development—regions with high winds and low populations—are also hundreds of miles away from existing transmission lines. In order to tap that wind energy, expensive transmission must be built to these regions.
- Environmental Impacts: Wind turbines are large infrastructures that must be mounted into the ground and connected to transmission lines. They produce no emissions from energy generation, but will have some impact on the environment though construction or operation. Wind turbines are known to cause bird deaths if they are located in the migration route of low-flying birds. Nevertheless, the Audubon Society officially supports wind power when proper environmental and wildlife standards are met. They note that bird kills resulting from wind turbines are probably many magnitudes less than bird kills resulting from strip mining, pollution, and eventually, from climate change (Allison 2007).
- Noise: Wind turbines also generate noise when operating, though the noise of large, industrial turbines is low frequency and does not carry over long distances. When wind projects are sited at required distances away from residential property, noise levels generated by the turbine and natural

background noise are less than EPA outdoor noise standards, and are roughly equivalent to the ambient noise of a quiet office or library (AWEA 2007).

- Interference: Radar and aviation impacts have also been a concern for larger wind projects that are located near airports or radar stations because the frequency of operating wind turbines can sometimes interfere with radar or radio equipment. Denmark's Middelgrunden Wind Project is near the Copenhagen airport, but air traffic controllers have a computer program that removes the frequency changes caused by the turbines (Spaven Consulting 2001). Though wind turbines can affect military radar, identifying and avoiding wind development near radar sites can mitigate this interference. The Department of Defense (DOD) recently released a report on the PAVE PAWS radar station in Massachusetts, stating that the proposed Cape Wind Project's site is outside of the 25 km off-limits zone and should not have any effect on the radar system (MDA 2008).
- Aesthetic Impacts: Another significant issue with wind energy development is its visual impact. Many residents who live near the proposed Cape Wind Project in Cape Cod, Massachusetts are concerned about their viewshed and strongly oppose the project. However, a recent survey in Vermont found that the majority of residents would support a wind project visible from where they live (Raab 2008). Opposition to wind based on aesthetic impacts may vary across regions and different populations.
- Property Value Impacts: Associated with aesthetic concerns is the potential that property located near a wind project may decrease in value. A 2003

study on wind development's impact on property values found no correlation between property value decrease and proximity to wind development (Sterzinger et al 2003). Even so, many residents are concerned with wind's potential impact on property values.

Solutions

Deepwater offshore wind technology would enable the U.S. to tap its vast offshore wind resource that exists over deep waters. Offshore wind technology that allows for wind projects to be sited far offshore can help alleviate many of the siting and permitting issues of building on land. Having an offshore wind project that is not visible from land bypasses the noise, aesthetics, and property value issues. This does not mean that offshore wind projects address all of the issues facing wind energy. Offshore wind projects affect marine ecosystems in addition to migratory birds, and can also affect the shipping and fishing industries, in addition to recreational sailing activities. However, careful planning and impact studies can mitigate environmental and other impacts.

A potential solution to the problem of wind intermittency is aggregation. Wind power output fluctuates because no one area will have constant wind speeds of high velocities that can turn a series of turbines without producing power fluctuations. Across a large geographical region, wind patterns will vary at different locations within the region so that at any given time in a large area, at least one location will have enough wind resource to generate power. Connecting areas of complementary wind regimes could reduce the power fluctuation caused by multiple wind projects. Though linking two projects will not provide complete stability, it is likely that such a linkage could provide a small amount of firm power relative to total capacity as well as lower fluctuations in power output. A number of studies on wind resources and interconnecting wind projects have found that interconnecting numerous projects significantly reduces intermittency.

It is important to note that there are other potential solutions for reducing variability, such as energy storage. The ability to store wind energy would allow for it to be dispatchable, a term that refers to sources of power that are available on demand. Currently, some storage methods are available in the form of pumped hydro, where wind power produced during times of low demand is used to pump water to higher altitudes. That water is then released to produce power during times of high demand. Pumped hydro is only available in select geographic locations such as Norway, and is not a realistic form of storage for many other parts of the world. Storage technology such as batteries, compressed air, and flywheels are being studied and improved (Denholm 2005). Most of these technologies are available on a smaller scale, and are not economically viable for large-scale storage. Because large-scale energy storage is still under development, this thesis focuses on interconnection as a viable solution for reducing the variability of wind power generation.

Thesis Overview

This thesis will explore the feasibility of creating a coordinated network of offshore wind projects within complementary wind regimes through examining technological feasibility, economic viability, and policy/planning issues of building such a network off the east coast of the U.S. Wind speed data for sites along the east coast of the U.S. are used to analyze the nature of offshore wind patterns and the benefits of interconnecting multiple wind projects.

The technological challenges facing coordinated networks of offshore wind projects fall under two categories: platform and mounting technology for deepwater conditions and transmission cabling technology. Offshore conditions in the U.S. are much more turbulent than most of the coastlines of Europe, and the continental shelf is deeper, possibly requiring floating wind technology for areas far enough away to be out of sight from land. Transmission is also an issue in terms of connecting offshore wind projects to the existing energy grid or to each other, but it is more of a financial than technical issue. Various types of transmission technology exist that are optimal for moving energy over varying distances and conditions. With offshore wind projects, the standard alternating current (AC) transmission lines are sufficient for connecting the wind project to the energy grid, provided the project is not sited hundreds of miles away from the nearest interconnection point. For purposes of interconnecting wind projects that are far away from one another, high voltage direct current (HVDC) may be a better solution. This paper will examine the various transmission options optimal for the hypothetical two-project network and estimate the cost of laying out these transmission cables.

Economic feasibility is a key part of any energy project. A major barrier to the implementation of deepwater offshore wind technology has been the high cost of producing new technology along with the high cost of installing large infrastructure offshore. Additionally, transmission lines are expensive to buy and install, especially underwater. This paper will attempt to estimate the costs of interconnecting two hypothetical offshore wind projects. These costs will be compared with the economic benefits of less variable power and more renewable energy generation vs. fossil fuel generation. While such technology may not be financially feasibly today, this paper will also identify the degree to which costs must come down in order for such projects to be feasible.

All energy projects have environmental and other impacts, and wind projects are no different. While policy and planning issues vary depending on site location, all wind projects will affect the environment, industries, and residents that live or use the land/water in which the project is located. Deepwater offshore wind projects would be located in federal waters and subject to the federal permitting process, which has currently been released in draft form by the Minerals Management Service (MMS). Wind projects must also apply for relevant state permits regarding cabling and interconnection to the grid. All of these factors make it extremely difficult to permit one offshore wind project, let alone an entire network of projects. The final chapter explores the policy and planning issues of creating an offshore wind network, and how the issue of variability can be incorporated into the permitting process.

The current wind siting process requires wind developers to propose and conduct feasibility studies on various sites, does not encourage development at sites that may be interconnected to decrease intermittency. Creating a coordinated network that optimizes reduction in variability would require the development of some sites with less-than-optimal wind resources. These sites would not be optimal for a developer in terms of maximizing profits from power sales, but are important for the integrity of the coordinated network. This kind of coordination would require a centralized method of gathering wind data and identifying linked sites that developers are encouraged to build on. Additionally, there would need to be incentives for developing specific sites as well as compensation for developing less than optimal sites.

California and Texas have both implemented programs to coordinate wind development on-land, and the Bureau of Land Management (BLM) has regional management plans for developing resources on public lands—including wind power. These programs may prove to be valuable precedents for a federal program targeting offshore wind development. Having such a federal program may also provide a way to implement incentives or other ways of encouraging the development of better, more cost efficient offshore wind technology that would make it technologically and economically possible to build networks of offshore wind to supply a significant percentage of the U.S. energy demand.

TECHNOLOGY

A coordinated offshore wind network can only be feasible if the appropriate technology is available. In the U.S., a coordinated network would require some projects to be sited in deeper waters that are far from shore. Offshore wind turbines have been built in shallow waters, but is the technology available for constructing them in deeper waters? A network of offshore wind projects would also require affordable transmission technology to connect the wind project to the power grid. This chapter will explore the status of wind power development and provide an overview of the available transmission options.

Status of Wind Power Development

Wind power has been harnessed for thousands of years to grind grains, pump water, and sail ships. Since old-fashioned wind turbines did not produce very much energy, up to 20 kilowatts (kW) by the end of the 1800's, wind energy was not looked upon as an efficient source of power in the early days of electricity generation (Ackerman 2000). However, wind power and water wheels were the two main sources of "power", and windmills were built all across Europe. Since wind power could not be stored and was not always reliable or easy to control, mills and pumps were powered by electricity from coal during and after the industrial revolution. Due to the large-scale generation potential of coal, gas, nuclear, and hydro power plants versus the small scale potential of wind turbines, developing wind power in the U.S. was not a priority until the oil crisis and the environmental movement in the 1970's brought to light the importance of energy resources and the negative consequences of relying on coal and other fossil fuels. Starting around the 1970's, renewed interest in wind power led to the research and development of larger and more efficient turbines. Between 1891 and 1958, the power capacity of a turbine increased from 18 to 100 kW. In the 50 years since then, the power capacity has increased 50 times to 5.0 megawatts (MW) (Ackerman 2000).

Wind energy is the fastest growing energy technology in the, with new technological advances as first generation wind projects are nearing the end of their production lifetime (DOE 2006). Not only are new wind sites being developed, but old wind projects are being replaced. Most of the world's wind energy development has occurred in Europe, which housed 76% of the world's wind energy production capacity as of 2003 (Ackerman 2005). The European Union's (EU) Commission on Energy has made the development of renewable energy the central aim of its energy policy. Prior to this, individual countries such as Germany and Spain introduced feed-in tariffs, a price guarantee for renewable energy that incentivized wind development. U.S. wind energy development expanded rapidly after 1980 with the implementation of state and federal tax credits that affected California in particular. Though the original wind turbines installed in the 1980-1995 era were generally poorly designed compared to today's turbines, their installation made wind development part of the California landscape and paved the way for improved turbine designs.

Wind power may be less than 1% of the U.S. energy supply, but the U.S. has the world's fastest growing wind industry (EIA 2007, Wiser and Bolinger 2007). The amount of installed wind capacity increased by 45% in 2007 (AWEA 2008). Though states on the east and west coast were quicker to adopt industrial scale wind development, the Midwest is now experiencing a boom in wind development. Furthermore, areas of Wyoming and the Dakotas have very attractive wind resource combined with low populations, making it possible to site large wind projects away from residential areas. However, there is no available transmission, fueling a debate on whether or not to invest in building transmission across multiple states. Individual states have such as California and Texas have both enacted policies to encourage developers to build wind projects, and many states in New England have new renewable portfolio standards (RPS) that have helped make wind power a fiscally attractive option.

Optimal Wind Conditions

Wind turbines generate power in relation to wind velocity. Different generators are manufactured to achieve optimal performance at a particular wind velocity, after which an increase in velocity does very little to increase power output. For example, the velocity to power curve for the REpower 5.0 MW turbine starts at 3.5 m/s, the minimum velocity for power generation. It achieves optimal performance when wind velocity is greater than or equal to13 m/s and stops generating power when wind speeds are higher than 25 m/s (REpower 2008).

On land, areas of good wind resource can deliver velocities of 10 m/s or higher for long periods of time. AWS Truewind has conducted extensive wind velocity modeling to produce a wind resource map of the U.S. showing average wind velocity. Average velocity can be used as a proxy for estimating average power output, but some locations experience fluctuating wind speeds. They may appear to have low average wind velocity when in reality the locations experience long periods of high wind velocity accompanied by periods of extremely low velocity. In general, average velocity is a strong indication of wind potential. In the U.S., areas with high average wind velocity are the Dakotas, mountainous areas in the Rocky and Appalachian Mountain ranges, parts of New Hampshire, Maine, Vermont, the Great Lakes, and offshore of New England and Alaska (Elliot and Schwartz 2006).

Wind resources are higher and more stable offshore, resulting in better power output. A wind turbine's power output has a cubic relationship to wind velocity, so a small increase in velocity can easily double or triple a turbine's power output. For example, a turbine operating in an area with wind speeds of 9 m/s will produce more than three times as much power as an identical turbine operating in an area with wind speeds of 6 m/s. This is because $9^3 = 729$, $6^3 = 216$, and 729 is 338% of 216. The same turbine stationed in a location with 50% higher wind speeds can produce more than three times as much power.

Wind Turbine Sizes and Design

Turbine sizes for U.S. on-shore wind projects vary in size from less than 100 kW turbines for small-scale applications to a few hundred kW for small-scale community level wind. Common turbine sizes are the 660 kW Vestas V90 turbine, the 550 kW G.E. turbine, and the 1.5 MW Vestas turbine. Offshore wind projects tend to have larger wind turbines than on-shore projects because offshore sites generally have more space and are less restricted by visual concerns. Larger turbines are more cost-effective, both in capital and installation costs. There are a number of large turbines that can be used for offshore wind projects, including the Vestas 3 MW turbine and REpower's 5 MW turbine

(RenewableEnergyAccess, 2006). Larger turbines are more visible from long distances and better suited for locations that are farther from the coastline (Watson 2007). The technology issue in offshore wind installation lies not in turbine technology, but in installation. Shallow-water foundations installed in water less than 30 m deep can be driven into the seafloor. In Europe, the coastline is within 30 m deep for 10-15 kilometers (km) offshore, while the US coastline is steeper, especially on the west coast, and many offshore areas with high wind potential have depths of more than 30 m (Leithead 2007).

Deepwater Offshore Technology

Offshore wind projects in Europe use gravity or monopile foundations similar to on-shore installations, but those foundations may only be economic in shallow water. Gravity bases can come in many shapes and are like anchors, using weight to keep the turbine securely in place. Monopile bases are rods driven into the ground, or in this case, ocean sediment, to secure the turbine (Elliott and Schwartz 2006). Tripods can be added to a monopile bases to increase stability, but cost more to manufacture and install. A foundation with a suction bucket can also be effective, especially in solid ocean-bottom. This is installed by putting a hollow "bucket" partway into the seafloor and pumping out the air inside the "bucket" to create a vacuum that will hold the turbine in place (Sclavounos 2006). An MIT group studying platforms for deepwater offshore wind turbines has, after extensive modeling, concluded that a 5 MW turbine mounted on a tripod platform with suction "buckets" at the seabed can withstand the various forces acting on the system (Sclavounos 2006). These include winds and waves as well as any seismic activity on the seafloor.

Though many studies are underway to research designs for deepwater offshore wind turbines, none have yet been constructed or installed commercially. This is in large part because wind turbines are so large, towering hundreds of feet high with a wingspan almost as wide. They are expensive experiments. A recent study of turbine prices found the average cost of wind turbines to be around $1.2 million/MW (Wiser and Bolinger 2007). Assuming that the cost of weatherproofing for offshore usage adds an additional 25%, it would cost $7.5 million for one 5 MW turbine alone. Constructing and testing a floating platform to support such a turbine would likely cost at least as much as the turbine itself. While academic groups may not be developing and testing such platforms, industry groups have the means to do so and are gaining interest. Stat Oil, a Norwegian petroleum company, has started a project to scale down an offshore oilrig for supporting a Siemens 2.7 MW turbine. The company has already collected data from testing the platform and the turbine separately, and the next step will be to test the dynamics of the two components operating together (Cruickshank 2008).

Talisman Energy, a British energy company, has developed the Beatrice Wind Farm Demonstrator Project in U.K. The Beatrice Project is comprised of two 5 MW turbines near the Beatrice oilfield in waters of up to 45 m deep and 25 km away from shore (Talisman Energy 2008). While the U.K. has implemented policies to encourage the development and testing of such new technology through monetary incentives, no such policies currently exist in the U.S., making it even more difficult for U.S. companies to conduct similar projects. While it is unlikely for there to be a federal policy incentivizing the development and testing of new offshore wind technology, it is possible that individual states with an interest in offshore wind may provide some incentives. Many individual states such as Massachusetts have programs that provide monetary support to renewable energy projects including offshore wind.

Transmission Technology

Offshore wind projects also require different transmission lines to connect the project to the grid. Since salt-water is a conductor of electricity, submarine transmission cables must be heavily insulated to prevent any leakage. Windy areas also have rough waters and can have rocky coastlines that quickly wear out transmission lines. The oil and gas industry uses low-voltage submarine transmission lines, but offshore wind projects would probably use high-voltage lines. High-voltage transmission lines are already expensive on land, costing around a million dollars/mile for medium voltage (33 kV), and double for higher voltage (72 kV). Submarine high-voltage cables could cost more than 2 million dollars/mile due to the high cost of insulation and installation (Wright et al, 2002). These costs are based on using AC transmission lines.

Many studies have concluded that AC transmission is the most cost effective method for offshore wind unless a wind project is over 300 MW or farther than about 25 miles from shore (Ackerman 2002). In those cases, HVDC lines may be superior because AC lines lose charge over long distances. Additionally, Direct Current (DC) lines are made of 2 wires, and are more stable than AC lines in that if one of two wires is damaged, the other wire can continue to deliver power. In AC systems, damage to the wire necessitates shutting down the whole segment for repairs (Gross 2008). HVDC lines have been used to connect long distances on land in parts of the U.S., but are uncommon because of their high cost and low flexibility. HVDC is optimal for connecting two points that are extremely far apart, but it is difficult and expensive to use DC lines to create a grid with multiple points. Despite their high cost, submarine HVDC transmission lines have been installed over long distances. The Itaipu HVDC Transmission Project in Brazil has a rated power of 6,300 MW with a voltage of around 600kV. It was built in the mid-1980's and is almost 800 km or about 500 miles long (Rudervall et al, 2000).

HVDC technology has already been implemented in the U.S. to transport power from Canada to New England. Additionally, the Long Island Power Authority (LIPA) and Neptune Regional Transmission System, LLC completed a 65-mile 500 kV HVDC undersea cable estimated to cost $600 million in 2007 (Hocker 2007). The Neptune cable allows Long Island residents to buy cheaper power from the PJM interconnection region, and has already saved $20 million during its first summer of operation (LIPA 2007). The Neptune cable is an example of using HVDC technology to transport a large amount of power between two points over a long distance. Creating a wind network would require more flexible technology that can connect multiple points over long distances.

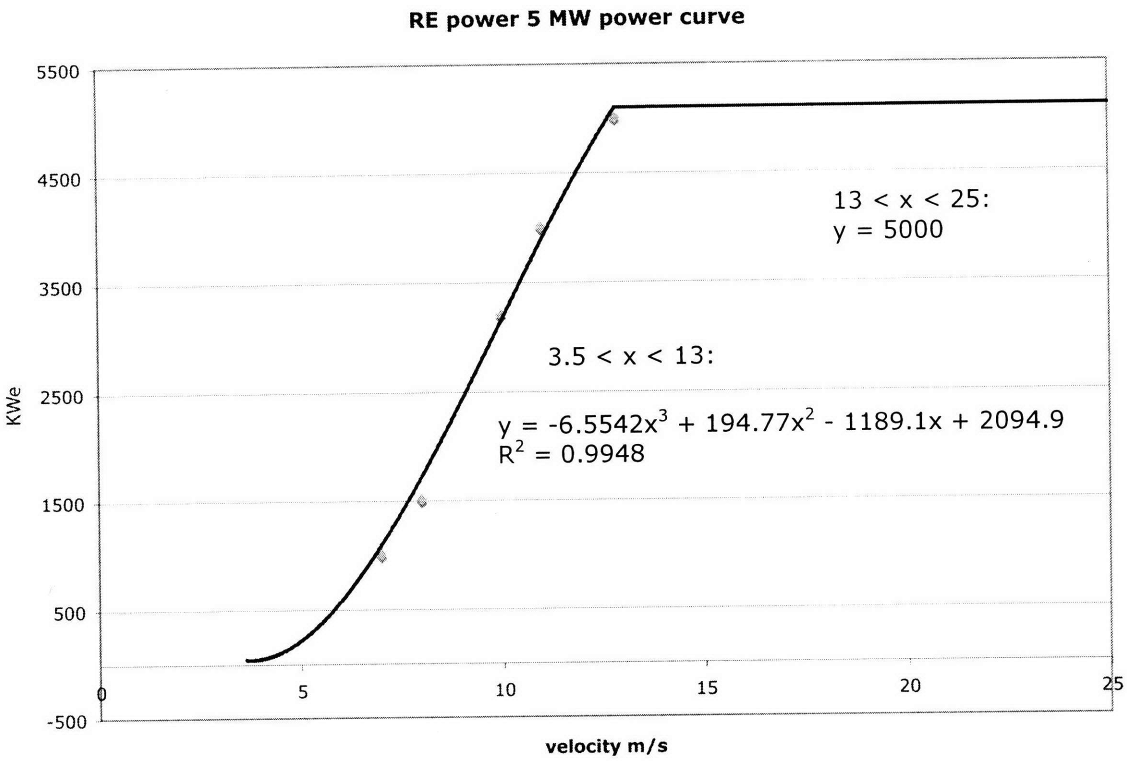
There are a number of different types of HVDC options that can handle multi-terminal systems, but all of them require a converter station at each terminal. Newer technology allows for bipolar HVDC lines that use 2 sets of conductors instead of three, thereby cutting costs. There are two main types of HVDC converters—current source converters (CSCs) and voltage source converters (VSCs). In general, VSC's are better at controlling active and reactive power independently of one another and gives greater flexibility in locating the converters within an existing AC network when linking a DC line to the existing energy grid. In terms of HVDC converter stations for offshore wind—there is currently one in operation in the North Sea, called the Troll A platform. For most offshore cases, converter stations must be powered by a stable energy source, usually diesel. The Troll A platform uses power delivered from shore to reduce carbon emissions and bypass the need for platform-based generation (Bahrman and Johnson 2007).

There is another option called HVDC light, which does not require a constant energy source, is more cost effective than conventional HVDC, and uses VSC's, allowing for greater flexibility. However, it is only viable for moving up to 300 MW of power and is currently unable to handle multiple terminals without additional converter stations (Skytt et al 2001). HVDC light is a promising technology for connecting offshore wind projects to the existing electric grid. New advancements in HVDC light technology may also enable it to be used for constructing an offshore grid of multiple projects without requiring new converter stations to be built with each additional connection to the HVDC line. Transmission technology is available for creating an offshore wind network, though some of the technology is relatively new and may improve in the near future.

ANALYSIS

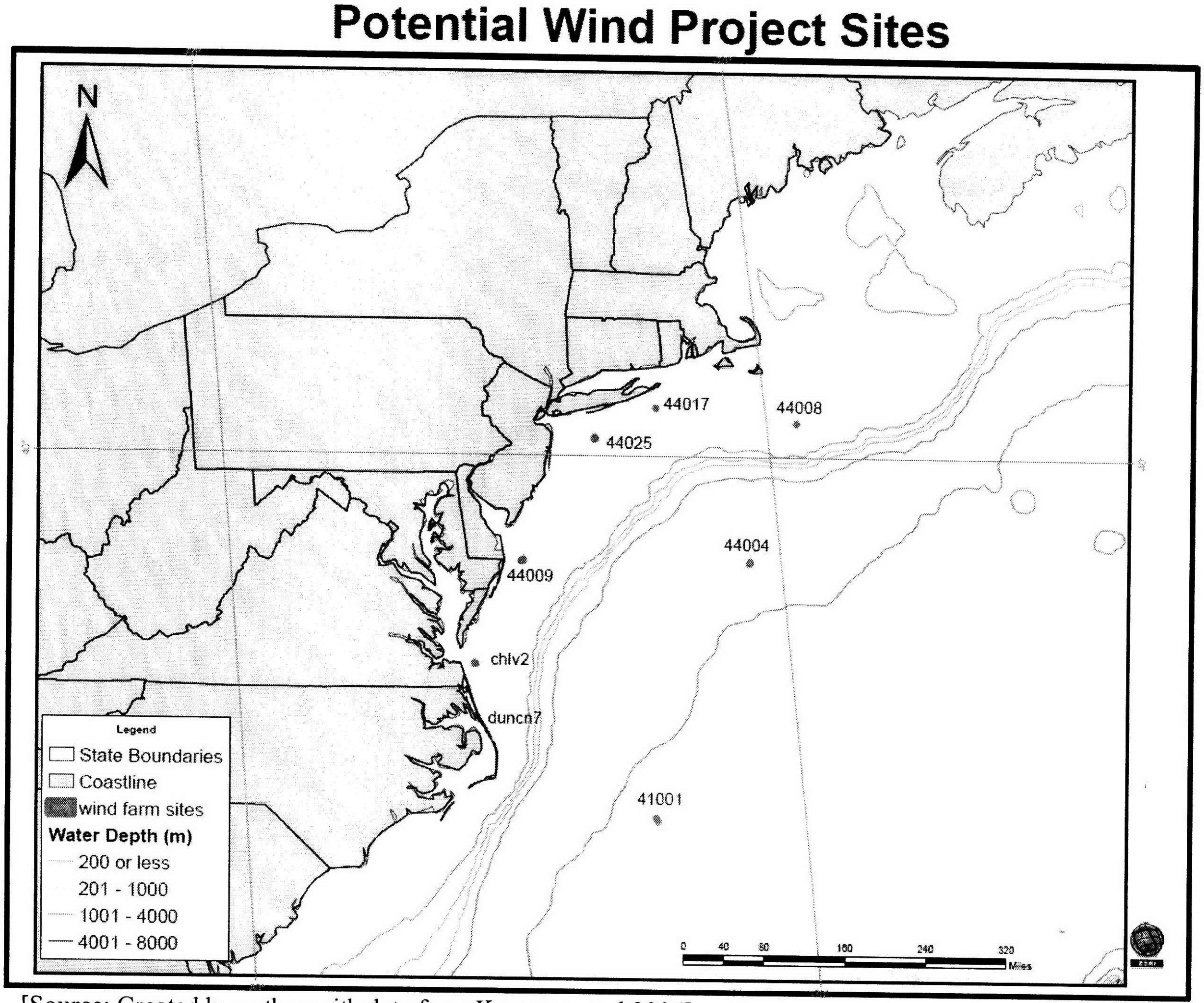
The dataset used for this analysis consists of hourly wind velocity data from 8 sites along the Mid-Atlantic Bight (a region of the Atlantic Ocean located off the East Coast of the U.S.) during 2003 and 2004 (Kempton et al 2005). The data were used to analyze the effects of intermittency and power fluctuation of wind projects, and assess the cost-effectiveness of using transmission lines for interconnection.

Wind power fluctuation is often referred to as "intermittency," which more accurately describes the times during which wind speeds are too low or too high for an installed wind turbine to generate power. The term "intermittency" is frequently incorrectly used to refer to power fluctuation during non-intermittent time periods—the main complication with reliably integrating large amounts of wind power into an electricity grid. Most industrial-scale wind turbines can generate power between a large range of velocities, but the power output at the minimum "cut-in" wind speed can be hundreds of times lower than the power output at the maximum "cut-out" wind speed. This analysis uses REpower's 5 MW wind turbine as the prototype for calculating power output, and a size of 600 MW or 120 turbines for each hypothetical wind project. The REpower 5 MW turbine has a cut-in speed of 3.5 m/s and a cut-out speed of 25 m/s (REpower 2008). The turbine's power curve is as follows:



[Source: Created by author with data from REpower 2008]

Both intermittency and power fluctuation were examined among all 8 sites. To compare intermittency and power fluctuation between individual sites versus interconnected sites, the results for the 8 individual sites were compared with results for all possible 2-site combinations of those 8 individual sites (28 total combinations). All 8 sites are from an area with similar wind regimes, so it can be hypothesized that interconnecting sites within the Mid-Atlantic Bight would not yield as much benefit in lowering power fluctuation as interconnecting one of these sites to another site from a different wind regime.



[Source: Created by author with data from Kempton et al 2005]

Offshore Wind Potential

The table below shows the results of an analysis of power production during peak and off-peak hours for the 8 sites along the Mid-Atlantic Bight. This analysis was based on a recent study by Cape Wind Associates, which found that the wind patterns at Cape Wind's proposed site are more than 70% peak coincident (Cape Wind Associates 2008). The Cape Wind study used the 10 highest demand hours ISO NE in 2006 and 2007 and calculated the expected capacity factor at the proposed site during those 10 hours. The dataset of 8 sites along the Mid-Atlantic Bight does not include 2006-2007, so the method could not be replicated. Instead, peak hours were identified by using the dates and times of the 10 highest demand hours in 2005-2007. During those three years, the hours with the highest demand were between 2pm to 6pm and the days of highest demand were between June 27th and August 5th (ISO New England 2007).

The table below shows that power output and variability during peak summer hours were about the same as the average for all summer hours, but the power output during the summer was lower than average output over the entire year. Summer hours also had more variability, averaging 143% in the summer versus 83% for the whole year.

	Peak Summer Hours*			**All Summer Hours****			**All Hours**		
	Capacity Factor (C.f.)	Avg power/hr (MW)	Coeff. of Variability (C.of Var.)	C.f.	Avg power/hr (MW)	C. of Var.	C.f.	Avg power/hr (MW)	C. of Var.
41001	47%	2.35	72%	40%	1.98	92%	51%	2.55	71%
44004	38%	1.89	111%	37%	1.86	102%	53%	2.65	73%
44008	16%	0.78	218%	15%	0.77	222%	41%	2.04	94%
44009	27%	1.35	122%	24%	1.20	138%	41%	2.06	89%
44017	23%	1.13	161%	22%	1.11	159%	45%	2.27	83%
44025	24%	1.18	149%	23%	1.17	145%	44%	2.22	83%
chlv2	19%	0.94	188%	25%	1.24	133%	42%	2.10	81%
duncn7	22%	1.11	121%	18%	0.91	151%	29%	1.46	91%
Average	27%	1.34	143%	26%	1.28	143%	43%	2.17	83%

* Hours between 2pm-6pm during June 27-August 25th

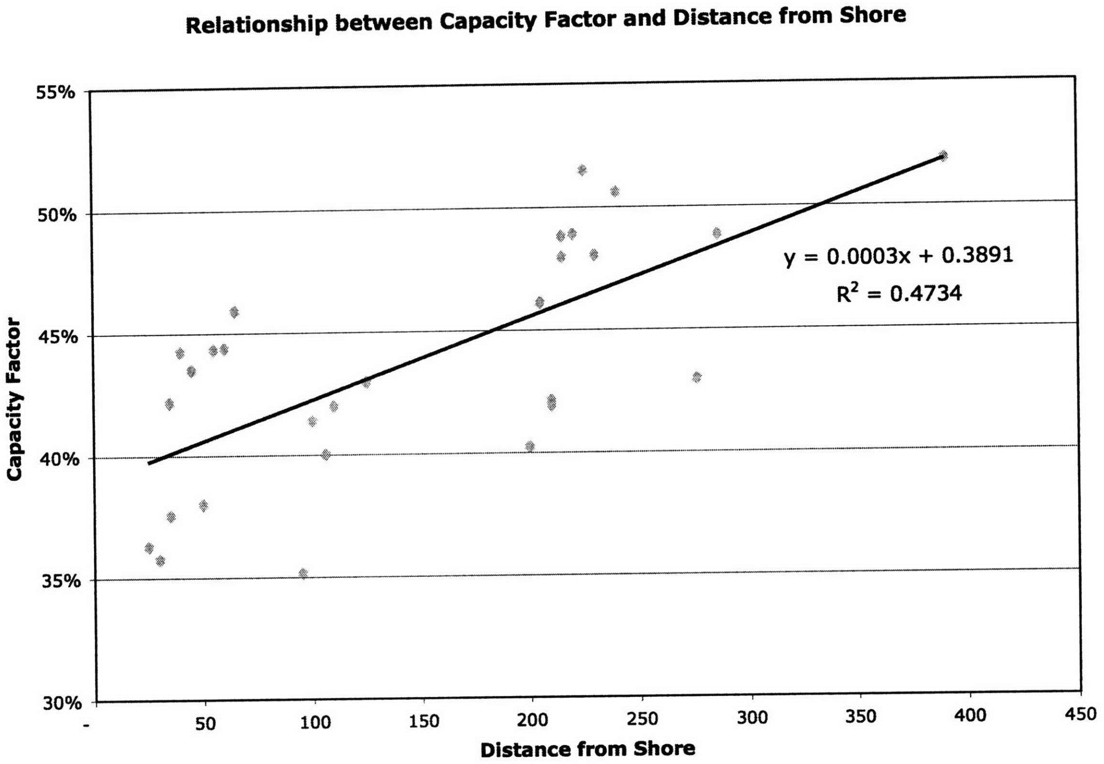
** All hours during June 27-August 5th

[Source: Created by author using data from Kempton et al 2005]

The difference between these results and the results for Cape Wind's proposed site could stem from different wind patterns between the sites or from the differing methods used to calculate peak coincidence. The Cape Wind study only used 10 specific hours as opposed to a block of hours over a 3-month time period. It is possible that Cape Wind's proposed site, which is not within the Mid-Atlantic Bight, happens to experience higher wind speeds during peak summer hours, while winds are stronger in the Mid-

Atlantic Bight during off-peak hours. These results are worthy of further study, and they highlight the importance of location-specific wind patterns in siting a wind project.

While offshore wind resources are generally higher than on-shore wind resources, it is also important to note that wind resources, and thus potential power output, generally increase with distance from shore. The graph below shows the relationship between distance and power output. Distance was measured with Geographic Information Systems software (GIS) using the Universal Transverse Mercator projection. Distance from shore for 2-project combinations was calculated by averaging the distance from shore of each individual project. Capacity factor was used as a measure for power output. Capacity factor is the proportion of actual expected power output to total possible power output, and is an indication of potential revenue from power sales and production tax credits (PTCs). A project with an average output of 2.22 MWh/hr for one wind turbine has a capacity factor of 2.22/5.0, or 44.4%.

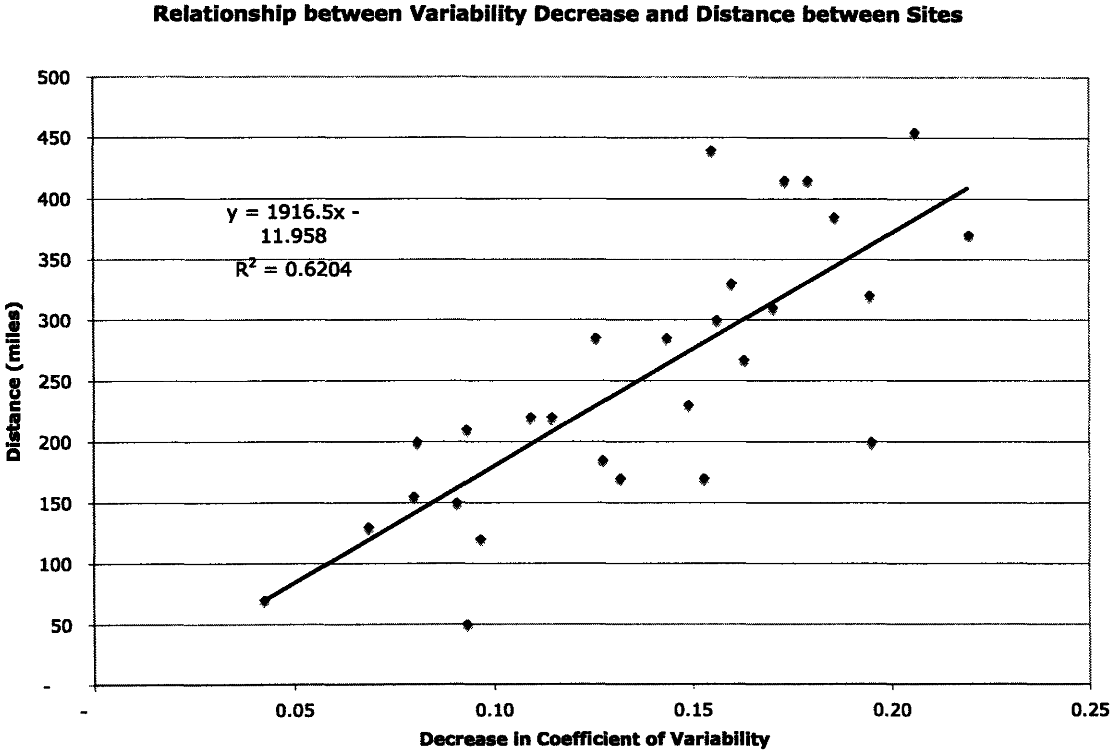


[Source: created by author using data from Kempton et al 2005]

Though transmission costs also increase with distance from shore, it is possible that, depending on the price of electricity and costs of transmission, increased revenue from higher wind resources may offset the higher transmission costs of building a wind project far from shore. The graph above illustrates that the relationship between distance from shore and power sales is linear, with an R^2 of 0.47. This shows that there is a trend of increased power sales as distance from shore increases.

Variability and Intermittency

Wind power is known for its intermittency and variability, but studies have shown that both intermittency and variability of a system of wind projects decreases as the wind projects within the system are sited with increasing distance from one another (UWIG 2000). The graph below shows the relationship between variability and distance between sites. The coefficient of variability was used as a measure of variability, and was calculated by taking the standard deviation of each dataset and dividing by the average power output for that dataset. All 28 of the 2-site combinations had lower coefficients of variability than the average coefficients of variability of their 2 individual sites. Sites that were farther apart also experienced a more significant decrease in variability, demonstrating that variability decreases as distance between sites increases.



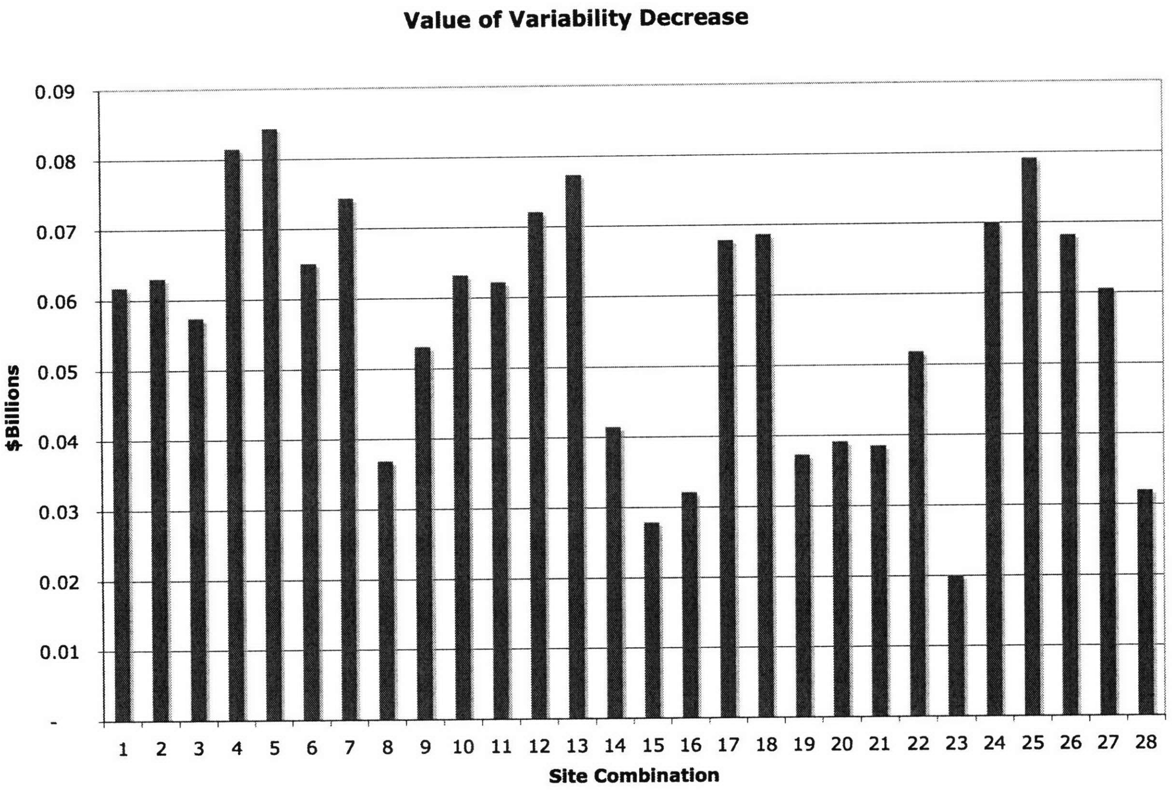
[Source: Created by author using data from Kempton et al 2005]

The linear correlation has an R^2 of 0.62, showing a very strong relationship between distance between sites and variability decrease. However, the sample size of 8 individual sites and 28 site combinations is not large, and adding more sites and creating more combinations over a larger geographical area could further strengthen the correlation. The potential to decrease variability via interconnection over long distances ranges from 4% to 22% with an average decrease of 8%. All 8 sets of data were from an area of similar wind patterns, and interconnecting wind projects over areas of differing wind patterns could result in a much higher decrease in the coefficient of variability.

Periods of intermittency also decreased with interconnection. Intermittent periods were defined as times when wind speeds were below the cut-in speed of 3.5 m/s or above the cut-out speed of 25 m/s. For the 8 individual sites, intermittency accounted for 8.7% to 15.6% of the year with an average of 12.2%. Intermittency for the 2-site combinations ranged from 0.8% to 5.8%, with an average of 3% and an average decrease in intermittency of 9.2% between individual sites and 2-site combinations. Interconnected sites not only experience less fluctuation in power output, but also experience fewer time periods of non-generation. See Appendix for detailed results of variability and intermittency decrease.

Value of Variability

An analysis of the cost-effectiveness of physically interconnecting multiple wind project sites was performed by comparing the value of variability reduction with the transmission costs of linking multiple sites. The cost of variability cannot be accurately determined on a per-megawatt basis, because such costs differ depending on the size of the power system, existing transmission capacity, existing generation capacity, supply mix, and load patterns. Numerous wind integration studies estimating the cost of integrating significant wind power from 10%-25% of a system's total demand estimate that these costs are on the order of $5/MWh (UWIG 2005). For this analysis, variability is assumed to have a cost of $5/MWh. Integration costs are incurred mainly through dealing with variability, such as costs for maintaining and using spinning reserves when wind speeds are low. Thus, integration costs are used as a proxy for the cost of variability. The value of tying two projects together is then calculated as the value of the decrease in variability between two separate sites versus two connected sites. The decrease in variability, in MWhs, is calculated by multiplying the decrease in the coefficient of variability by total power output by 240 turbines over 20 years. This figure is then multiplied by $5/MWh to find the value of the decrease in variability. For all 28 site combinations, the value of decreased variability ranged from $20 to $80 million. See Appendix for more detailed calculations. This method of calculating the value of variability uses integration costs as a proxy, but there are other, more accurate methods that could yield higher values for variability decrease. Calculating the impact and value of variability decrease could be more accurately done by using load data and analyzing how the decrease in variability actually impacts a region's load. Another method would be to use a transmission model to predict the impact of large-scale wind development, and how that impact decreases as variability decreases though interconnection. Lastly, interconnecting wind projects can increase the amount of firm power production, which could significantly increase the value of interconnection.



[Source: Created by author using data from Kempton et al 2005]

Interconnection Costs

Wind project development requires transmission for interconnecting individual wind projects to the existing grid, and interconnected projects would require additional transmission for linking the projects together. Transmission costs include cabling, installation, and other infrastructure costs such as converter stations and transformers. For the purposes of interconnecting two sites, it is assumed that submarine AC cabling was used to connect the two sites together, while one submarine DC cable was used to connect the AC cable to shore. DC cabling is not conducive to linking multiple generators together but is optimal for connecting two points with minimal transmission losses over long distances. Connecting both wind projects to the grid using one DC cable also allows for more control over power fluctuations because power delivery through a DC line can be controlled carefully (Conant 2008).

Costs for AC cabling were taken from the Cape Wind Draft Environmental Impact Statement released by the Army Corps of Engineers in 2004 (Army Corps of Engineers 2004). In order to arrive at 2007 costs, the cabling costs from 2004 were increased in relation to the increase in copper prices from 2004-2007. Since transmission cables are mainly made of copper, the change in price of copper is a good proxy for cabling prices[1]. The same method was used to adjust the pricing for DC cabling from 2003 data using cost estimates for an offshore wind project in Slupsk, Poland (Gross 2008).

The incremental cost of interconnection was calculated by taking the total cost of transmission for an interconnected system and subtracting the cost of individual connections for the two sites. Individual site transmission costs were estimated assuming AC transmission, and used the same method used to calculate AC transmission costs for an interconnected system. The costs for individual grid connection were mainly for AC cabling, an offshore substation, and grid interconnection. The incremental cost of transmission for interconnecting different paired sites ranged between \$0.5 and \$4.0 billion, which is significantly larger than the variability benefits of \$20 to \$80 million.

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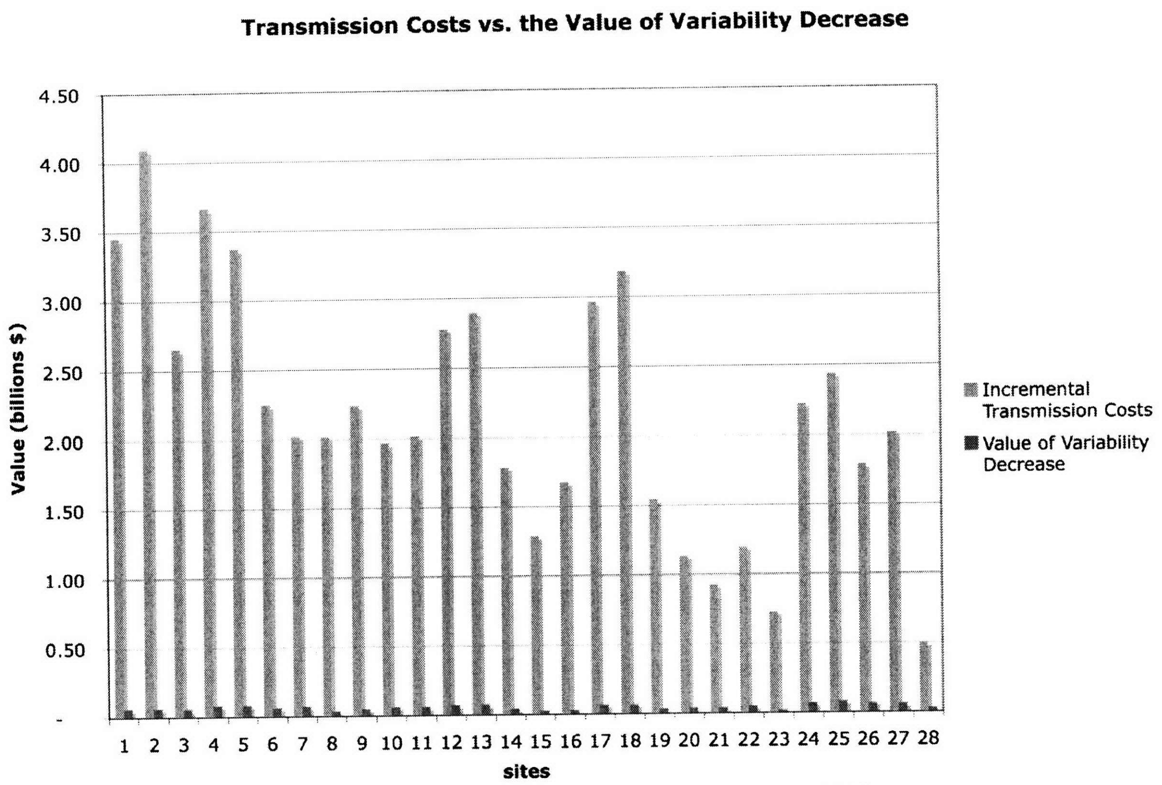
[1] Between 2004 and 2007, copper prices increased 50% on the London Metal Exchange. Between 2003 and 2007, copper prices increased by 75% (Bloomberg 2008).



[Source: Created by author using data from Kempton et al 2005 and Gross 2008]

Though the incremental transmission costs are significantly higher than the value of decreased variability, other factors also affect the viability of a wind project network. A project's distance from shore affects transmission costs and turbine installation costs. Distance from shore is also related to water depth, and any sites located in depths of approximately 50 m or more would require expensive deepwater foundations.

Three 2-site combinations, shown in the table below, were examined in greater detail in terms of their variability decrease, location, and the cost-effectiveness of interconnection. All three sites were within 100 miles of shore but differed in distance between sites and level of variability decrease as a result of interconnection. They were selected as examples of low, medium, and high variability decrease. See Appendix for results for all 28 combinations.

Site Combination	Variability Decrease	Distance from Shore (miles)	Distance Between Sites (miles)
40017 + 44025	Low—4%	65	70
44009 + chlv2	Medium—10%	35	120
44017 + duncn7	High—22%	50	370

[Source: Created by author with data from Kempton et al 2005]

These three site combinations represent the lowest and highest variability decrease among all 28 sets, as well as a medium variability decrease case. The low variability combination, with a variability decrease of 4%, also had the shortest distance between sites. The value of a 4% decrease in variability for those two sites was $20 million, but incremental transmission costs were $730 million. For the pair of sites with a 10% variability decrease, the value of variability decrease was $40 million while the incremental transmission costs were $930 million. For the pair of sites with the highest variability decrease of 22%, the value of variability decrease was $80 million while the incremental transmission costs were $2.4 billion. In these three cases, the incremental transmission costs were respectively 37, 23, and 30 times larger than the value of decreased variability.

Though the costs of interconnection via transmission lines are significantly higher than the value derived from reducing variability, interconnection does result in less fluctuation of wind power output. If transmission costs were lower, or if the value of wind power and variability increased significantly, interconnection may then be cost-effective. However, transmission costs are unlikely to decrease given that the price for commodities such as copper have increased in the past 5 years (Bloomberg 2008). Additionally, the incremental cost of transmission interconnection is so much larger than the value gained from reducing variability that transmission costs would need to decrease by more than 95% for this to be cost-effective. Realistically, interconnection via transmission lines is not a cost-effective option for reducing variability, but physical interconnection is not the only possible method for creating a coordinated wind network. In the U.S., interconnection to the same grid management region could yield similar benefits and not require expensive offshore transmission lines. In this case, variability reduction would be accomplished through siting projects in complementary locations rather than connecting projects with transmission lines.

For future wind development in the northeastern United States, offshore wind is a viable option based on its high wind potential. New technology for deepwater installations and cheaper transmission lines would enable widespread offshore wind development, along with higher electricity prices and the continuation – and enhancement – of incentives to support renewable energy. Additionally, any tax on carbon would make wind power more cost-effective compared to fossil fuel generators. For wind power to meet a significant portion of demand, challenges with wind integration need to be addressed. Coordinated siting, with an aim toward reducing variability, could decrease the impact of fluctuating wind production on the grid.

POLICY, PLANNING, AND RECOMMENDATIONS

Planning a network of wind projects in locations with complementary wind patterns can reduce the variability in wind power output, as long as these wind projects are all connected to the same electric grid. A network of offshore wind projects can be created by connecting multiple offshore wind projects to an offshore grid, or by connecting individual wind projects to the same or connected on-shore grid. In either case, the reduction in variability created by a coordinated network depends on the interaction between wind patterns at each site. A network comprised of sites with high complementarity will have lower variability than a network of sites with low complementarity. Thus, it is important that all wind projects within a network be sited in coordination with wind patterns of other sites. Variability of a network of wind projects decreases with the number of interconnected sites, as well as with distance between sites. A coordinated network that spans a large geographical area and includes numerous wind projects would have lower variability than a coordinated network spanning a small area with few projects.

One major impediment to integrating large quantities of wind power into the electric grid is the fact that wind power is variable, and the grid can only handle a certain amount of variability. However, current methods of calculating wind variability do not incorporate the decrease with variability due to the interaction of multiple wind projects. Adding two large wind projects in locations with high complementarity would create less variability than adding two large projects in locations with low complementarity. Current wind integration studies do not look at site-specific wind patterns or how that information could be used to reduce wind power variability.

A Coordinated Network for the U.S.

In the U.S., the electric grid is divided into multiple control areas, but power can be moved across control areas. Due to the high cost of offshore transmission cabling, it is likely more cost effective to create an offshore wind network in the U.S. by using the existing electric grid. Doing so would tie offshore and on-shore wind projects into the same grid, allowing for the creation of a coordinated wind network that includes both on-shore and offshore projects. A first step in creating a coordinated wind network in the U.S. would be to gather wind data for existing and potential wind project sites. This is already required as part of a development's feasibility studies, but this wind data is used to measure capacity factor and power output patterns for an individual site. The siting process does not take into account how the power output of a new project would increase or decrease the overall variability in a region's wind projects.

Building the optimal network in terms of lowering variability may require a top-down planning approach in which an entity collects wind resource data and conducts environmental studies to identify a set of sites that, if all developed, would complement each other and significantly reduce the variability in power output. In the U.S., wind developers are responsible for identifying potential sites and applying for permits with no guarantees that permits will be issued. The permitting process can take years, with multiple levels of permits required depending on a site's location and interconnection point. Most offshore wind projects would be located in federal waters, but would still need to obtain state and local approval for transmission interconnection. Projects located within state waters would be responsible for meeting state and local requirements for energy developments. Due to the uncertain nature of permitting, siting an entire network of sites would be a huge risk for any developer. The risk might be worth it if there were substantial rewards for building a wind network that has lower variability.

Alternatively, reducing the level of risk could enable the development of an effective coordinated wind network. The permitting issue could be bypassed if multiple sites for a coordinated network were all permitted at once, though this would shift the responsibility of identifying and applying for sites from the developer onto the entity responsible for permitting. The task of identifying sites for a coordinated network is more difficult than identifying individual sites. In addition to the fact that every site in the coordinated network must be viable with regard to environmental conditions, transmission accessibility, and economic impact, each site must possess wind patterns that complement the wind patterns of other sites. This task could be completed by an agency such as the Minerals Management Service that is already in charge of permitting offshore wind sites, by a task force comprised of representatives from the public and private sectors, a group of academic researchers, or some combination thereof. The Offshore Wind Collaborative convened by the DOE, the Massachusetts Technology Collaborative, and GE is an example of such a task force.

Having a task force responsible for identifying sites does not bypass the problem that the sites must obtain permits, file environmental impact reports, and go through a public notice and comment period. Though it might be possible to synchronize the permitting process of all sites within a coordinated network, each site will differ in location and face different obstacles in the permitting process. There would also be the question of what to do with the sites after they are identified. Would there be incentives offered to encourage developers to apply for permits? Would an agency undertake the permitting of all of the sites and then auction them off to developers?

The current siting and permitting process in the U.S. allows citizens to voice their opposition to large infrastructure projects, and a coordinated wind network comprised of many sites would need to be examined on a site by site basis in terms of environmental and community impact. There is no way to pre-permit or pre-approve a set of sites without undermining the current permitting process. A top-down planning approach in which an entity conducts an extensive wind resource study, identifies a set of sites for development that meet permitting standards, and guarantees permits for these sites may work in other countries that follow such an approach. In the U.S., however, opportunities for public input are an important part of any rulemaking or siting process. Though a permitting process that allows for public input and opposition can stall the process and prevent or delay the development of renewable energy projects, the process can also be an opportunity to examine and deal with new issues. It also ensures that those who suffer losses as a result of new development are fairly compensated. The development of a coordinated offshore wind network should follow existing standards for public involvement in the permitting process. If a network of sites meets all environmental and other permitting requirements, then public acceptance is the wildcard in whether or not these sites will be approved in a timely manner.

Public opposition to wind projects is often related to visual, noise, environmental, and economic impacts. Even if a proposed site has obtained permits through the appropriate agency, citizen or environmental groups can challenge the decision in court. While many delays in wind project permitting are the cause of disputes over environmental impacts prior to construction, citizens are sometimes strongly opposed to living near a large wind project (ECONorthwest 2006). Offshore wind projects located beyond the line-of-sight from the horizon would avoid visual and noise concerns that make it so difficult to site an on-shore wind project in New England. Siting farther from shore also reduces the number of citizens impacted for non-aesthetic reasons such as fishing and sailing. However, offshore wind projects must still meet environmental standards and address economic impacts on fishing, shipping, or other uses of the ocean. Though it might be possible to obtain permits and public acceptance for an entire network of offshore wind project sites, the process of identifying and permitting a set of sites would require support from government agencies on the permitting side as well as private companies to develop the projects. Wind projects in New England historically have a very difficult time obtaining permits without the projects getting moved or decreased in size. Even if the process of determining sites for an optimal coordinated network is done with greatest care to rule out sites that have negative impacts on the environment or on citizens, there is no way to ensure public support.

Every proposed offshore wind project in the U.S. has generated grassroots opposition (Cruickshank 2008). Because the current permitting process is a site-by-site process, planning for a coordinated network that spans a large enough geographical area would entail communication and collaboration between different states and regions. It would require a framework for interested stakeholders, state governments, federal agencies, and industry representations to create a plan for locating the right sites and getting the necessary support for development. The ability to prioritize sites within the optimal network may enable the permitting of at least some of the sites so that the creation of a network is not an all or nothing endeavor. Sites with high likelihood of permitting success, wind potential, and wind patterns that contributed to decreasing variability could be marked as high priority for development. This would still not yield an "optimal" network, but could be a promising starting point.

A viable way of incorporating the benefits of complementing wind patterns may be to identify zones of high wind potential and incorporate a variability component into the permitting process. Encouraging offshore wind development over many geographical zones will reduce variability. Adding a variability component to the permitting process will shift focus onto how a newly proposed wind project will play into a larger network of installed and proposed wind projects. Proposals for energy generators must already include documentation that the developing entity seriously considered a number of other alternative sites and provide an explanation of why the proposed site was the best out of the ones considered. Considerations include environmental impacts, economic impacts, electricity production, interconnection feasibility, and project cost. Including variability impact as a consideration may encourage developers to consider their proposed projects as part of a larger wind network with the goal of integrating large amounts of wind power while minimizing its impact on the grid.

Identifying zones of high wind potential over many geographical areas will also encourage wind development in general. There is already precedence for such proposals encouraging on-shore development of renewable resources. The Clean Energy and Economic Development Act, introduced to the senate in 2007, called for the designation of National Renewable Energy Zones (Senate Bill S.1531 2007). These zones would be identified as areas with good renewable energy resource, such as regions with high solar or wind potential and would be connected to the grid via transmission lines that facilitate renewable energy development. This idea is based on the Competitive Renewable Energy Zones (CREZ) in Texas, which are areas of high wind potential that are not located in environmentally protected regions or in populated areas. The Texas Public Utilities Commission facilitates the construction of necessary transmission infrastructure to support new development by providing an expedient process for a utility company to recuperate transmission costs through rate changes (Totten 2008). This could be done on a regional level to encourage the development of a coordinated wind network that minimizes variability while providing renewable energy. As transmission infrastructure is upgraded and more wind power is installed, wind integration costs may decrease as forecasting methods improve and as grid operators become more familiar with managing wind energy.

The Supergrid

A coordinated wind network could also span multiple countries to take advantage of different wind regimes over large areas. In 2006, Airtricity proposed the Supergrid, a grid of offshore wind projects that could service the EU. This proposal was presented to the EU in 2006 and is still under development. It is a long-term goal that would require the cooperation of the EU, national governments, and multiple wind developers. By linking offshore wind projects spread out over the North Sea, the English Channel, the Bay of Biscay, and the Celtic Sea, the Supergrid would provide stable, renewable energy to numerous European countries along the coasts. The Supergrid could supply a significant amount of electricity demand for the UK, Germany, Norway, Denmark, the Netherlands, Belgium, France, Spain, Portugal, and Ireland (Airtricity 2006).

The EU has set goals to encourage renewable energy development, and offshore wind technology was pioneered in Europe. Though the Supergrid is oftentimes referred to as a stable power source, it is important to note that there would still be some amount of variability in its power output. Even so, it would have significantly lower variability than individual wind projects. European energy policies that provide high prices for renewable energy make Europe a likely place for successfully implementing an offshore wind network.

The idea of connecting multiple wind regimes to create a network of wind projects with low variability could also be developed in other areas of the world, both offshore and onshore. Ideal locations to connect together would be areas where the wind patterns are complementary and are separated by short distances. These would need to be identified via more extensive studies of wind patterns. Other potential areas for coordinated wind networks could be countries with large onshore grids such as China or the U.S., where the existing grid already spans multiple areas with different wind patterns. In the U.S., the wind patterns in California are different than those in Texas, the Dakotas, and the Midwest. Linking all of these regions together could significantly lower variability. However, all of these regions are managed by different grid operators, and jurisdictional issues would need to be overcome.

Recommendations

The successful implementation of a coordinated offshore wind network requires stronger incentives for renewable energy development, increased investment in developing transmission infrastructure, and more public and political support for wind power. Policies that provide incentives for renewable energy development could help make offshore wind more economically viable and encourage more developers to propose and develop more offshore wind projects. Such incentives may also encourage developers to try building new technology that enables deepwater offshore wind development.

Many states have RPSs requiring that a certain percentage of electricity demand be provided from renewable sources. Electricity providers are required to submit a certain amount of renewable energy credits (RECs) to fulfill RPS standards, and these RECs have a per MWh value that adds on to the value of electric power sales from a renewable energy generator. REC values vary by state and depend on the RPS standards. Increasing RPS standards to require higher percentages of renewable energy generation to meet demand would increase REC values, effectively increasing the value of renewable energy, and higher RPS standards could boost wind power development, both on-shore and offshore. A tax on carbon could have a similar effect in rendering renewable energy more cost-effective than other types of generation. Though a tax on carbon would not increase the value of renewable energy like an RPS, it would increase the cost of fossil-fuel generation such as coal or natural gas. In comparison, renewable energy would become more cost effective and be seen as a better investment.

In addition to monetary incentives to support renewable energy, transmission upgrades are necessary to adequately support new renewable energy development. There have been many proposals and reports examining ways to strengthen the grid and provide transmission access to areas of high wind potential. Significant wind integration at 10% or 20% of energy demand cannot be successful without extensive transmission infrastructure upgrades. This includes new transmission as well as upgrading existing lines to a higher voltage, and wind integration reports estimate that transmission upgrades for integrating 20% electricity from wind would cost around $25 billion (DOE 2008).

The Clean Energy and Economic Development Act, legislation proposed in the Senate in 2007, would enable transmission development by allowing a transmission provider to quickly recover costs associated with capital investments that facilitate renewable energy development (Senate Bill S.1531 2007). Strengthening the existing electric grid increases its ability to support more variable power sources such as wind. Providing new transmission to areas of high wind potential would make it possible to tap more wind resources such as the high winds in the Dakotas and parts of the Midwest. Strengthening transmission connections to Quebec would enable access to a vast resource of wind and hydroelectric power. Hydro-Quebec has a hydroelectric portfolio of 41,000 MW, with an additional 2,800 MW of hydroelectric power and 2000 MW of wind power under development (Brosseau 2008). The limiting factor in importing renewable energy from Quebec is the capacity of transmission infrastructure.

Assuming that there is adequate transmission to support significant offshore wind development and that it can be cost-effective in the U.S., the lack of a well-defined permitting process has delayed or prevented offshore wind development. In 2001, Cape

Wind Associates proposed to build the first offshore wind project in the U.S. off the coast of Cape Cod. Seven years later, the MMS, the agency with authority over the federal process for wind energy, has released an environmental impact statement for Cape Wind. The MMS also released draft rules for offshore renewable energy permitting in July of 2008, and hopes to conclude the public comment period and release the final rule by the end of 2008 (Cruickshank 2008). For the permitting process to include a component on variability decrease and wind patterns, the MMS would probably need to consult grid integration experts, representatives of Independent System Operators (ISOs), and the National Oceanographic and Atmospheric Administration, which has been collecting oceanic wind data for decades. A clearly defined offshore wind permitting process coupled with stronger monetary incentives to support renewable energy would help enable the development of a coordinated offshore wind network, but public support for such projects is also crucial.

Public acceptance of offshore wind has grown considerably since the Cape Wind Project was proposed in 2001. The Cape Wind Project stirred up controversy because of its location near the Cape and Islands. The opposition has been focused primarily around visual impacts and environmental ramifications, but environmental impact assessments have found that the project would have negligible or minor negative impacts on the environment. The Audubon Society has come out in favor of Cape Wind, and public support for Cape Wind has increased over time. For example, 42.4% of Cape Cod residents opposed the Cape Wind project in 2005, but by 2008, less than 23% of residents opposed the project (Firestone and Kempton 2007, Civil Society Institute 2008). In a statewide poll conducted in 2008, an overwhelming 87% of residents supported the Cape

Wind Project (Civil Society Institute 2008). The MMS took comments for their draft Environmental Impact Statement in 2008, and 90% of which were positive in favor of Cape Wind (Gordon 2008). If support for Cape Wind is any indication of the public opinion of offshore wind in general, then the outlook is good for new offshore wind development, especially at further distances from shore. The successful development of an offshore wind project may garner increasing public support, as would more public awareness of climate change issues and renewable energy solutions. Strong public support would enable the development of numerous offshore wind projects. This, combined with a permitting process that incorporates wind patterns and variability decrease as a factor in project siting, could make coordinated offshore wind networks a reality.

Conclusion

Offshore wind power is a large, significant, and untapped resource in the U.S., especially off the east coast where there is little land for on-shore wind power development near demand centers. As awareness of climate change increases, renewable energy generation has become a topic of interest in public and private sectors. One main problem with wind energy is that wind projects fluctuate, making large amounts of wind energy a difficult resource to integrate into the grid. Wind power variability can be decreased by siting multiple wind projects over large geographical areas with complementary wind patterns and creating a coordinated offshore wind network.

The technology for creating a coordinated wind network is available. Wind turbines have been installed offshore in parts of Europe for years, and research on deepwater offshore wind technology shows that floating wind projects can be built to tap offshore resources in deep-water (Sclavounos 2007). New transmission technology allows for long-distance cabling using HVDC lines that are cheaper and more easily connected to multiple generators than traditional DC lines, which are optimal for long distances. An analysis of the costs of interconnecting two offshore wind projects shows that the transmission costs of interconnection far outstrip the monetary benefits of reduced variability from interconnection. In the U.S., however, physical interconnection is not necessary to realize the benefits of interconnection. Multiple wind projects can be connected to the existing grid instead of requiring a separate offshore grid. Thus, interconnection to reduce variability becomes a siting issue that can be achieved by identifying groups of sites that collectively have low variability or by incorporating variability impacts into the permitting process of individual wind projects. Incorporating variability as a factor in the siting process adds little additional cost and can ease the burden of integrating large amount of wind power into the grid. Combined with transmission upgrades and better forecasting techniques, the idea of creating coordinated offshore wind networks is a realistic concept that has the potential to supply a significant amount of energy demand for the eastern U.S.

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APPENDIX

Calculating Coefficient of Variability

Decrease in Coefficient of Variability from interconnecting sites 44009 and 44017:

$$CoefficientVariability = \frac{stdev_{dataset}}{mean_{dataset}}$$

$$stdev_{44009} = 1.83$$

$$mean_{44009} = 2.06$$

$$CoefficientVariability_{44009} = \frac{1.83}{2.06} = 0.89$$

$$stdev_{44017} = 1.9$$

$$mean_{44017} = 1.94$$

$$CoefficientVariability_{44017} = \frac{1.89}{2.27} = 0.83$$

$$Average = \frac{0.89 + 0.83}{2} = 0.86$$

Coefficient of Variability for interconnected sites 44009+44017 is 0.8, so the decrease in coefficient of variability from interconnection is 0.86-0.80, or 6%.

Intermittency Decrease

Individual Sites

Site ID	% Generating	% Non-generating
41001	89.9%	10.1%
44004	91.3%	8.7%
44008	85.4%	14.6%
44009	87.6%	12.4%
44017	88.6%	11.4%
44025	88.1%	11.9%
chlv2	87.3%	12.7%
duncn7	84.4%	15.6%
Average	87.8%	12.2%

Intermittency Decrease

Site Combinations

Site Combination	% Generating	% Non-generating
41001+44017	99.2%	0.8%
44004+44025	98.5%	1.5%
41001+44004	98.3%	1.7%
44004+chlv2	98.2%	1.8%
41001+44025	98.1%	1.9%
41001+chlv2	98.1%	1.9%
44004+44017	98.1%	1.9%
44017+ducn7	98.0%	2.0%
41001+44008	97.7%	2.3%
41001+44009	97.7%	2.3%
44004+ducn7	97.6%	2.4%
44017+chlv2	97.6%	2.4%
44025+ducn7	97.6%	2.4%
44025+chlv2	97.5%	2.5%
44004+444009	97.3%	2.7%
41001+ducn7	97.1%	2.9%
44008+ducn7	96.7%	3.3%
44009+44017	96.7%	3.3%
44004+44008	96.6%	3.4%
44008+chlv2	96.4%	3.6%
44009+44025	96.2%	3.8%
44008+44009	96.2%	3.8%
44008+44025	96.0%	4.0%
44009+ducn7	95.8%	4.2%
44008+44017	95.7%	4.3%
44009+chlv2	95.0%	5.0%
44017+44025	94.8%	5.2%
chlv2+ducn7	94.2%	5.8%
Average	97.0%	3.0%

Value of Variability Decrease

An example of calculating the value of variability decrease for sites 44009 and 44017:

$$Cost_{Integration} = \frac{5\$}{MWh}$$

$$CoefficientVariation_{44009+44017} = 0.8$$

$$Cost_{Integration(44009+44017)} = \frac{5\$}{MWh} \cdot 0.8 \cdot \frac{power\_output}{turbine} \cdot \# \, turbines$$

$$Cost_{Integration(44009+44017)} = \frac{5\$}{MWh} \cdot 0.8 \cdot \frac{381{,}519 MWh}{turbine} \cdot 240 = 366.3 million\$$$

$$CoefficientVariation_{44009} = 0.89$$

$$Cost_{Integration(44009)} = \frac{5\$}{MWh} \cdot 0.89 \cdot \frac{360{,}800 Wh}{turbine} \cdot 120 = 192.7 million\$$$

$$CoefficientVariation_{44017} = 0.83$$

$$Cost_{Integration(44017)} = \frac{5\$}{MWh} \cdot 0.83 \cdot \frac{398{,}396 MWh}{turbine} \cdot 120 = 198.4 million\$$$

$$Cost_{Integration(44009)} + Cost_{Integration(44017)} = (192.7 + 198.4) million\$ = 391.1 million\$$$

$$Cost_{Interconnected} - Cost_{Individual} = (391.1 - 366.3) millions\$ = 24.8 million\$$$

Variability vs. Incremental Transmission: Full Results Table

Site Combination	Capacity Factor	NPV power+ PTC	Incremental Transmission ($billions)	Variability Decrease (%)	Variability Decrease ($billions)	Distance between Sites (miles)	Distance from Shore (miles)
41001+44004	51.9%	6.81	3.46	13%	0.06	285	390
41001+44008	43.0%	5.59	4.09	15%	0.06	440	276
41001+44009	42.2%	5.48	2.65	14%	0.06	285	210
41001+44017	48.1%	6.29	3.66	18%	0.08	415	230
41001+44025	48.0%	6.28	3.37	19%	0.08	385	215
41001+chlv2	46.2%	6.03	2.25	15%	0.07	230	205
41001+ducn7	40.3%	5.22	2.02	20%	0.07	200	200
44004+44008	48.9%	6.40	2.02	8%	0.04	155	286
44004+44009	49.0%	6.41	2.24	11%	0.05	220	220
44004+44017	50.7%	6.65	1.96	13%	0.06	170	240
44004+44025	51.5%	6.76	2.02	13%	0.06	185	225
44004+chlv2	48.9%	6.40	2.78	16%	0.07	300	215
44004+ducn7	42.0%	5.45	2.90	19%	0.08	320	210
44008+44009	40.1%	5.19	1.78	11%	0.04	220	106
44008+44017	43.0%	5.59	1.29	7%	0.03	130	125
44008+44025	42.1%	5.47	1.68	8%	0.03	200	110
44008+chlv2	41.4%	5.37	2.97	17%	0.07	415	100
44008+duncn7	35.2%	4.52	3.19	21%	0.07	455	95
44009+44015	44.4%	5.67	1.54	9%	0.04	210	60
44009+44017	43.6%	5.78	1.13	9%	0.04	150	45
44009+chlv2	42.2%	5.48	0.93	10%	0.04	120	35
44009+ducn7	35.8%	4.60	1.19	15%	0.05	170	30
44017+44025	46.0%	6.00	0.73	4%	0.02	70	65
440017+chlv2	44.4%	5.78	2.23	16%	0.07	330	55
44017+duncn7	38.1%	4.92	2.44	22%	0.08	370	50
44025+chlv2	44.3%	5.77	1.79	16%	0.07	267	40
44025+duncn7	37.6%	4.85	2.02	17%	0.06	310	35
chlv2+duncn7	36.4%	4.68	0.50	9%	0.03	50	25