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THE ECONOMICS OF OFFSHORE WIND ENERGY

by

Caitlin M. Howland

A Thesis Submitted in Partial Fulfillment
of the Requirements for a Degree with Honors
(Economics)

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University of Maine

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Abstract

The global community is yearning for a solution to climate change. Research has shown one cause of climate change could be emissions from electricity production by fossil fuel sources. Deepwater offshore wind energy is being looked into as a potential solution, and with every new endeavor a cost analysis is necessary.

To conduct this study I reviewed reports, articles, and papers by economists, potential developers, and by research institutions and universities. I took this information and applied it to my own calculations on the cost of hypothetical deepwater offshore wind development in the Gulf of Maine. I found it important to consider two types of costs, both social and private. Learning curve effects play a major role in a decreasing cost over time. External costs can be added to private costs by applying a government tax on carbon, done through pricing carbon. I used three different pricing schemes. When compared to natural gas by a means of levelizing the costs of energy (LCOE), the most aggressive carbon tax caused the LCOE of offshore wind to be competitive by 2030.

Offshore wind will not be viable in the coming years without a carbon tax and a potential government subsidy. If no developers invest in a farm, learning curve effects will be stunted and not be able to take the course of action predicted. The effect of learning-by-doing over time is crucial to decreasing costs. If an aggressive pricing scheme on carbon is adopted, it is possible deepwater offshore wind energy could become competitive in less than two decades.

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I. Introduction

Climate change is a serious issue. It affects every single living creature on the planet. Generally, these effects are negative ones. Climate change is also full of uncertainties. When is it going to happen? At what point will the damage become serious? Is it already serious and the world just does not know it yet? Governments worldwide realize this phenomenon is a problem demanding attention, and yet there is no serious legislation in the global sphere addressing this issue. It is a characteristic of human nature not to look too far beyond one’s own lifespan, however this issue insists foresight happens, and that it happens soon.

Governments, scientists, and engineers alike are looking toward solutions for the future. In a perfect world, for the United States this solution would address the climate issues, do the least harm to the environment possible, and at the same time contribute to the political, but unattainable, solution toward a perfect economy with energy security. A policy balancing all three elements has not been done before, but people are thinking, and progress is being made. Offshore wind could be one of these solutions. This is especially true on the state level for Maine.

The goal of this thesis is to develop a logical procession in which to analyze the costs of offshore wind and then calculate estimates aligning with the Maine Offshore Wind Plan (DeepCwind). This thesis aims to explain basic concepts of the technologies currently in place in Europe and then the technologies planned for the Gulf of Maine.

This rational procession will come to show how, if utilized, this resource can and will be viable in the future for the state of Maine and through what forces this will most effectively occur.

The first offshore wind farm was completed in 1991 off the coast of Denmark. This farm consisted of eleven-turbines with each turbine rated at 450kW. In the beginning, offshore turbines were relatively close to shore, and were modeled after onshore turbines. By 2010, there were forty-five wind farms off the cost of European countries providing an estimated 10.6 TWh of electricity to the grid (European Wind Energy Association 2011). The idea of offshore wind in the US has been circulating for years. Cape Wind was the first project to take off in the US, but has been bogged down in litigation disputes for years. Construction for Cape Wind was originally set to begin in 2004 with an estimated completion year of 2005. Most of this resistance has come from the Alliance to Protect Nantucket Sound.

The Maine Public Utilities Commission issued a request for proposals for "Long-term Contracts for Deep-Water Offshore Wind Energy Pilot Projects And Tidal Energy Demonstration Projects" in September of 2010 (Maine Public Utilities Commission n.d.) Statoil North America Inc. submitted an application in September of 2011. To eventually be able to connect to the Boothbay substation, Statoil has also applied to the New England Grid operator, ISO New England (bangordailynews.com). DeepCwind currently has completed the permitting process and it leasing a plot of ocean for a test turbine to be deployed at the beginning of the summer in 2013.

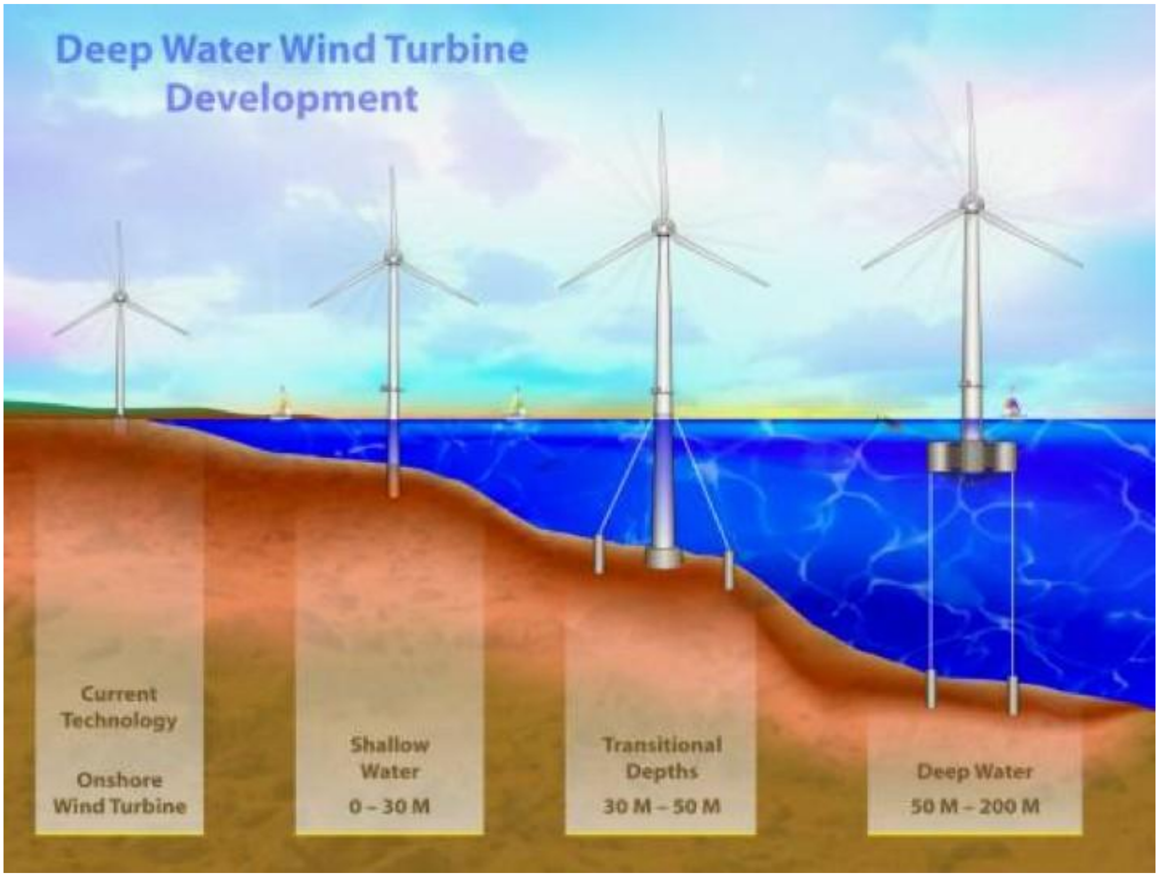
The scope of this thesis is strictly in regards to economics. Engineering and climate science relate to the topic, but are outside this thesis's scope. This thesis is primarily focused on estimating and inferring costs based strongly on primary sources. William Nordhaus and Nicholas Stern are economists who have extensively studied this topic, and much of their research is used throughout the thesis. Various universities, such as the University of Delaware, the University of Massachusetts' Renewable Energy Research Lab, as well as the University of Maine's Advanced Structures and Composites Center, have done extensive research on topics related to this thesis, and these institutions are often referenced.

This thesis will begin with a chapter giving an overview of turbine technologies currently available and undergoing research. There is a race for the first deepwater floating wind farm in the world right now, and this technology is also covered. This is followed by an assessment of the natural resource potential for the state of Maine. Also in this chapter is an explanation of calculations related to expected energy output that will be utilized in the following chapter on private costs. The private cost chapter uses a method called levelizing the cost of energy to obtain a cost per kilowatt-hour. At this point, it is necessary to bring in another energy source, for this thesis natural gas, to be able to compare pricing. Natural gas fired electricity generation is a reasonable technology for comparison because it often sets the electricity price in New England and has been a significantly growing source of electricity generation in New England during the last decade. The same method is used to levelize this cost of energy as well. The social costs chapter adds to the private costs the external costs related to carbon emissions and their impact on climate change damages. Estimates from both Nordhaus and Stern are used for these external costs. The penultimate chapter discusses how the estimated social costs could be translated into federal policy. The final chapter presents conclusion

II. Technology Overview

Offshore wind energy is divided into two main categories: shallow water and deepwater. There are also transitional depth foundations, but these are very similar to shallow water, so here the two technologies will be grouped together. Deepwater is usually defined as over 60 meters or 200 feet in depth, and shallow water as anything less than that. Structures in shallow water use fixed-based technology whereas in deepwater, a floating structure is required. Floating wind turbine technology is in its infancy stages and currently, no deepwater floating wind farms exist in the world. The concept for floating platforms was adapted from the offshore drilling industry and other marine technologies. Floating platforms are well used, but the idea of combining them with turbines for floating wind energy generation is young. On the other hand, shallow water turbines are considered to be a mature industry. They have been in operation in Europe and other parts of the world since the early years of the century, and many countries in Europe consider offshore wind electricity generation one of their main sources of energy. Figure 2.1 is a depiction of offshore wind turbine development. This diagram was created in 2006, and therefore the “current technology” label is outdated. Figure 2.1 provides a visual for the differences between wind turbine technologies at different depths.

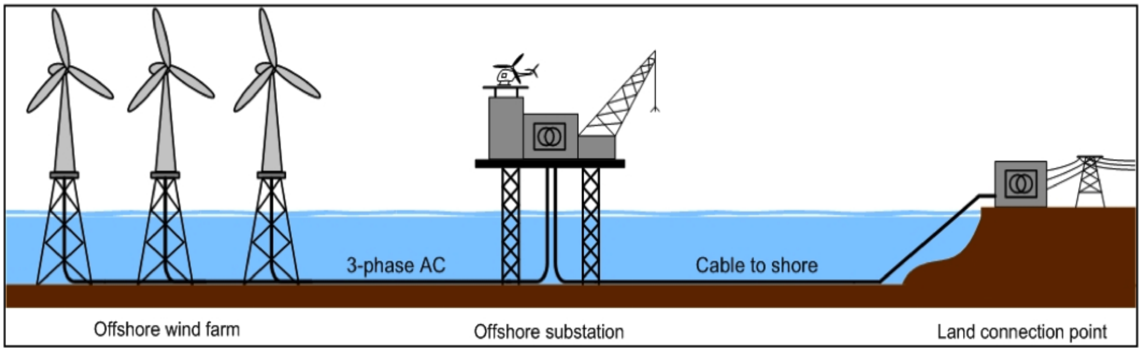
Figure 2.1 Deep Water Wind Turbine Development



Source: (Robinson and Musial 2006)

Wind farms, whether deepwater or shallow water, have the same basic components. They have turbines with nacelles, hubs, and blades. These are connected to towers, which connect to foundations that are moored to anchors with mooring lines. A cable connects the structures to an offshore substation, which then runs one cable to the shore. This cable runs into the land connection point where the electricity is then fed into the grid, and from there to homes. Figure 2.2 is a general depiction of the components for an offshore wind farm. The connection of the turbines to land is key because without it the electricity generation goes nowhere. The farm shown in figure 2.2 is a simplification, but shows the offshore wind farm, the offshore substation, and the land connection point.

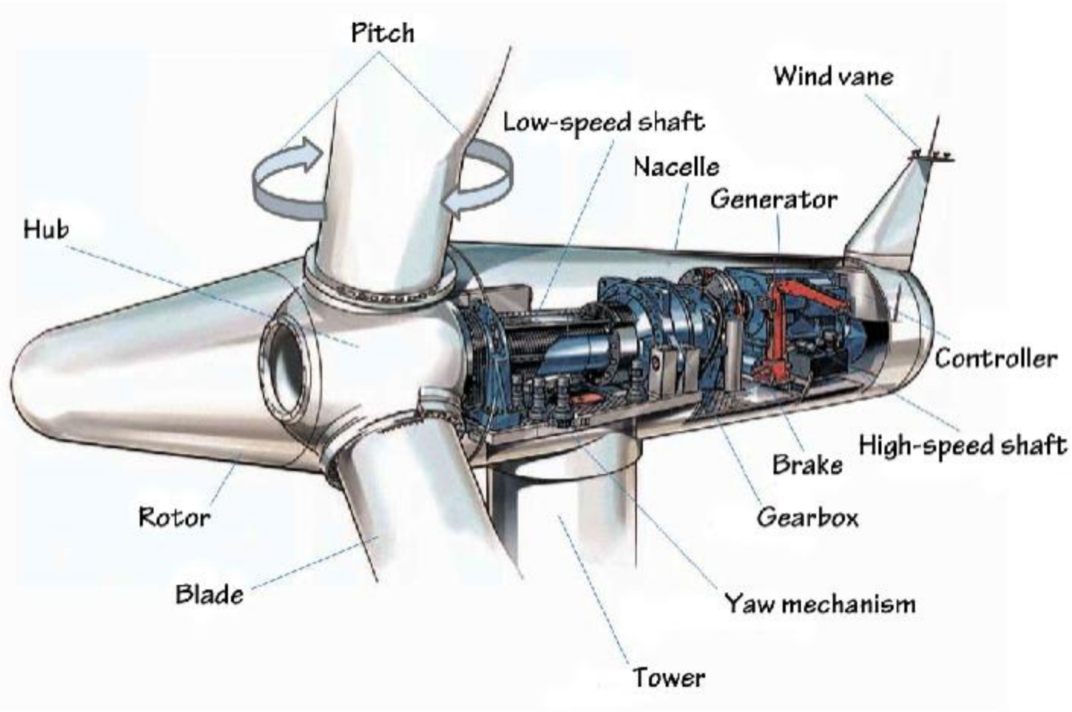
Figure 2.2 Overview of Wind Plant Components



Source: (AWS Truewind, LLC 2009)

This is not a thesis on the engineering behind wind turbines, but it is important to have an overview of where the energy actually comes from. The wind turns the blades, which are pitched a certain way depending on the resource. This is the raw energy. This energy is then transformed into electricity, usable in homes, through a series of gears and the generator. The blades are pitched to slow the turbine if the resource is too strong for the mechanics of the technology to prevent a failure of the technology. There are also brakes for emergency shutdown of the turbines. The whole package on top is called the nacelle, and this is mounted on a tower that is mounted on a foundation or a platform. A breakdown of the major components of the nacelle is provided in Figure 2.3. Knowledge of all the functions of each part is not necessary for this thesis. It is however useful to have a general understanding and idea of what comprises a wind turbine and this is provided by Figure 2.3.

Figure 2.3 Major Components of a Wind Turbine

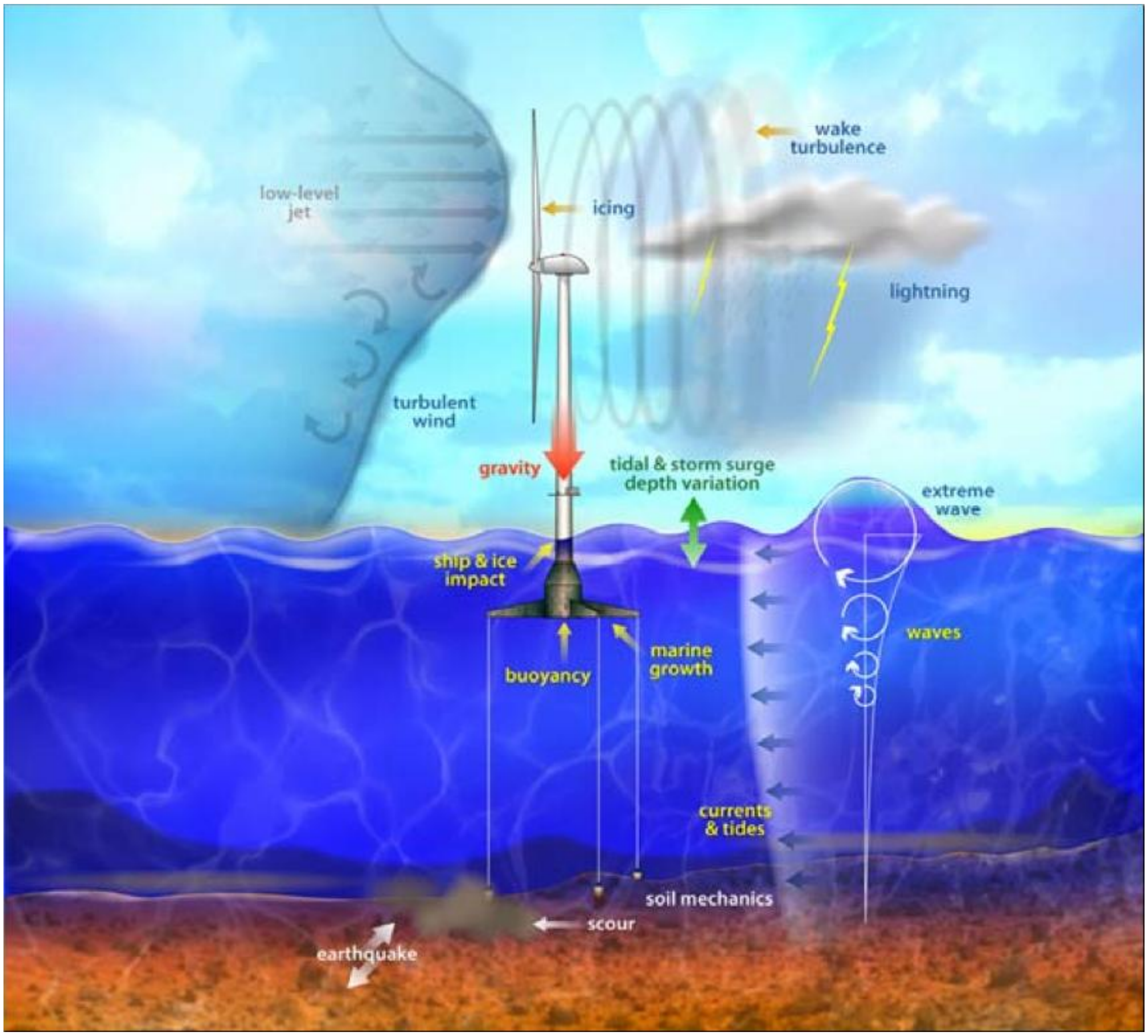


Source: (U.S. Bureau of Labor Statistics n.d.)

Parameters for Offshore Technology

When building a structure for the harsh offshore environment, many challenges arise. Environmental conditions of interest over a project's lifetime include wind, wave, current, water depth, soil, seabed characteristics, and ecological conditions. These conditions translate into more specific factors engineers work to counteract. These factors, depicted in Figure 2.4, include low-level jet streams, icing, lightning, turbulent wind, wake turbulence, gravity, tidal and storm surge depth variation, extreme waves, ship and ice impact, buoyancy, marine growth, waves, currents, tides, soil mechanics, and scour.

Figure 2.4 Forces on a Floating Turbine



Source: (Robinson and Musial 2006)

Discussing wind elements is not only important for structural and design aspects of the turbine, but also for the future potential energy production. The importance of the wind resource as it pertains to the costs of energy is discussed in the subsequent chapter.

The wind resource also influences the layout of the wind farm. Wind data is collected on site using meteorological towers, commonly called met towers. Parameters for wind data include wind speed, preferably measured at the hub height in annual, monthly, hourly, and sub-hourly increments. Wind speed frequency distribution is the number of hours per year within each wind speed interval. Wind shear is the spatial rate of change of wind speed in the vertical direction. Scientists also measure the intensity of turbulence using the standard deviations of wind speeds sampled over a given period of time as a function of the mean speed. The wind direction distribution also plays a role as do extreme wind gusts and return periods.

Waves are important to the design of the structure because it must be able to withstand certain load forces. Waves are important on a logistical level as well, seeing as they affect the means by which projects are accessible. Wave height is defined as four times the square root of the zeroth-order moment of the wave spectrum. Significant wave height is one of the key parameters regarding waves. Other statistics of interest include extreme wave height, generally measured as the highest one percent of all waves, and the maximum observed wave height. Wave frequency and direction as well as the correlation between wind speeds and direction are also calculated and measured.

Currents come in two types. There are near surface currents, affected by the wind, and sub-surface currents from tides, storm surges, and atmospheric pressure variations. Currents cause scouring on foundations of offshore turbines due to their ability to transport sediment such as sand and waves. Currents affect sea bottom conditions and characteristics as well as apply forces to floating platforms in operation and support vessels during construction or maintenance.

Seabed characteristics and water depth vary between locations and specific projects. It is common for the depth of water to change over the area that makes up a wind farm. Every aspect of the technology is affected from the turbine to the tower, the substructure, and the foundation. The bathymetry affects the size of the structure and its exposure to hydrodynamic forces. The soil characteristics change which foundations and anchors are suitable. Sediments and subsurface descriptions include soil classifications, vertical and horizontal strength parameters, deformation properties, permeability, and the stiffness and damping parameters.

This data is collected prior to the beginning of construction on a project. It contributes greatly to the estimates on energy production potential, ultimately affecting the economic viability of the project. At the conception of a project, early data is gathered from previous climatological data and regional patterns. If the project continues, more precise data is necessary and specific studies are conducted. These studies generally last between a year and three years. To collect the wind data, met towers with either wind anemometers, LIDAR or SODAR are used. Metocean and geotechnical information are collected using other various technologies.

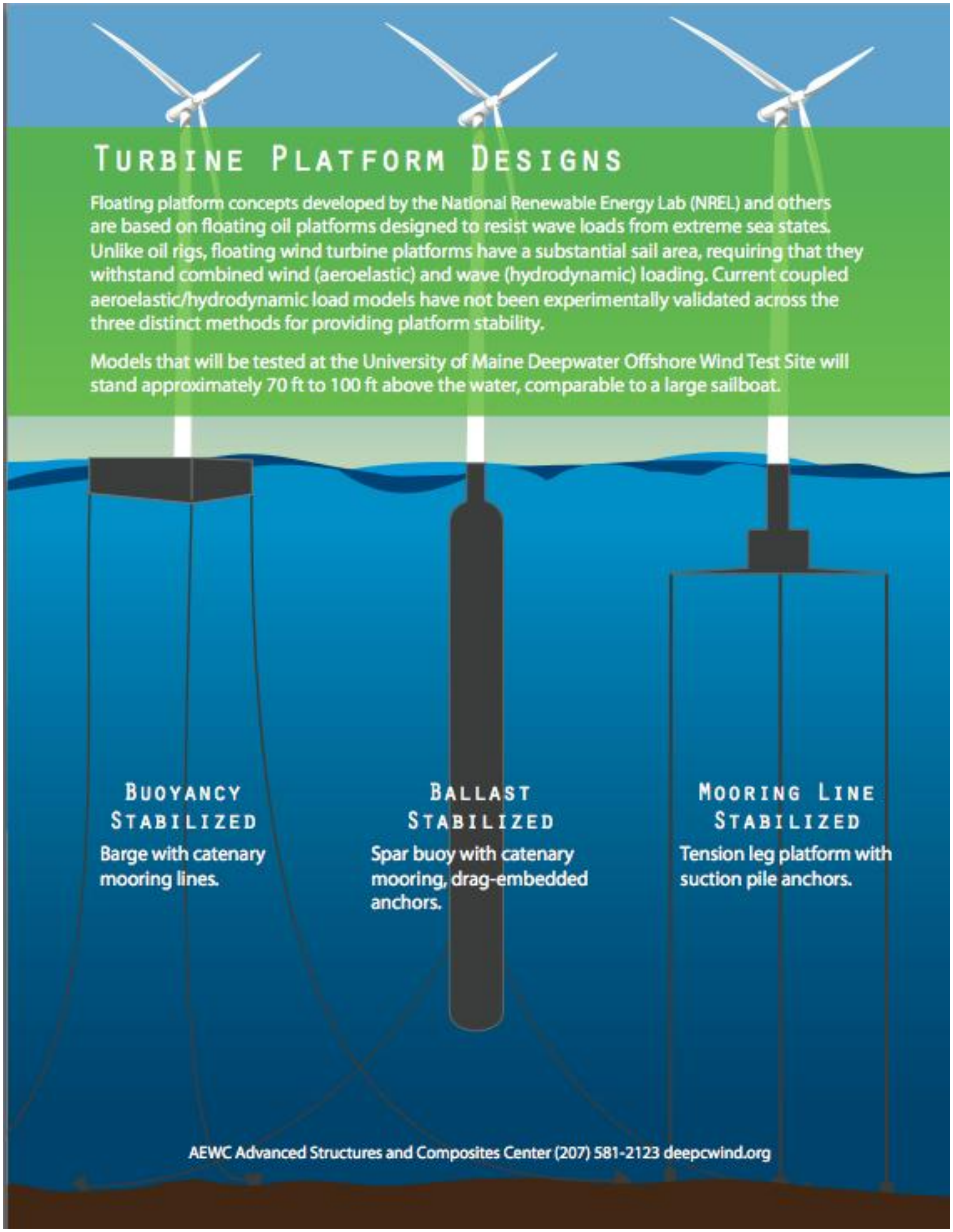
Certain parts of a turbine are more sensitive to specific factors. The rotor and nacelle are the most sensitive to atmospheric conditions. The support structure is the most sensitive to hydrodynamic and seabed conditions. Designs reflect these challenges. Specific projects also affect the design. Different places have different elements and engineers have to cater to these specifications.

One of the biggest struggles with the deepwater turbine industry is the lack of data surrounding the designs. Most of the engineering for offshore designs was adapted from the offshore oil and gas industry. Locations for drilling rigs vary from relatively shallow water to water much deeper than the wind industry is currently considering making this information a vital resource to the offshore wind industry.

Deepwater Platform and Foundation Designs

In the deepwater offshore wind industry today, there are three main designs for floating platforms each based on viable offshore oil and gas technology. There are different variations of these three designs being developed in the industry but usually the designs do not stray from the basic buoyancy-stabilized, ballast-stablized or mooring-stabilized standards. The National Renewable Energy Laboratory has studied each these three designs for use in supporting a wind turbine. The three basic platform designs are shown in Figure 2.5.

Figure 2.5 Floating Platform Designs



Floating platform concepts developed by the National Renewable Energy Lab (NREL) and others are based on floating oil platforms designed to resist wave loads from extreme sea states. Unlike oil rigs, floating wind turbine platforms have a substantial sail area, requiring that they withstand combined wind (aeroelastic) and wave (hydrodynamic) loading. Current coupled aeroelastic/hydrodynamic load models have not been experimentally validated across the three distinct methods for providing platform stability.

Models that will be tested at the University of Maine Deepwater Offshore Wind Test Site will stand approximately 70 ft to 100 ft above the water, comparable to a large sailboat.

Barge with catenary mooring lines.

Spar buoy with catenary mooring, drag-embedded anchors.

Tension leg platform with suction pile anchors.

AEWC Advanced Structures and Composites Center (207) 581-2123 deepcwind.org

Source: (DeepCwind Consortium 2012)

The National Renewable Energy Laboratory has also published a few other variations. These are variations on the aforementioned designs, but are more specific to what certain companies are developing.

The buoyancy-stabilized designs, which include the semi-submersible design and the barge, are moored with catenary mooring lines. The concept for this design is similar in principle from that of boats anchored to the seabed. The platform has a fairly significant footprint, and the slacked lines allow it to move up and down with the waves and shift slightly with changes in the wind.

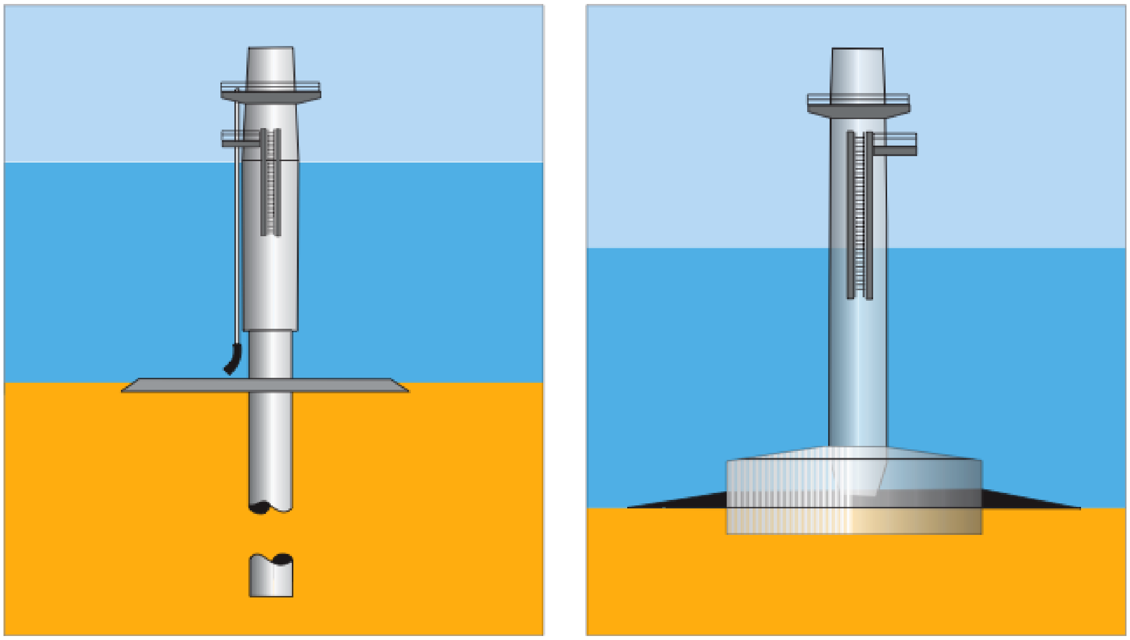
The ballast-stabilized design is a spar-buoy also utilizing catenary or taut mooring lines. Spar technology, which consists of a hollow tube containing an extremely heavy weight at the bottom, achieves stability by placing the structure center of gravity below the center of buoyancy providing the ability to counter-act the forces the turbine encounters.

The mooring line stabilized design, otherwise called the tension-leg platform, uses tensioned cables to stabilize the platform. This type of design is very stable for offshore wind applications, however, this design requires the most secure mooring of all three designs and necessitates very expensive anchors.

Fixed Platform and Foundation Designs

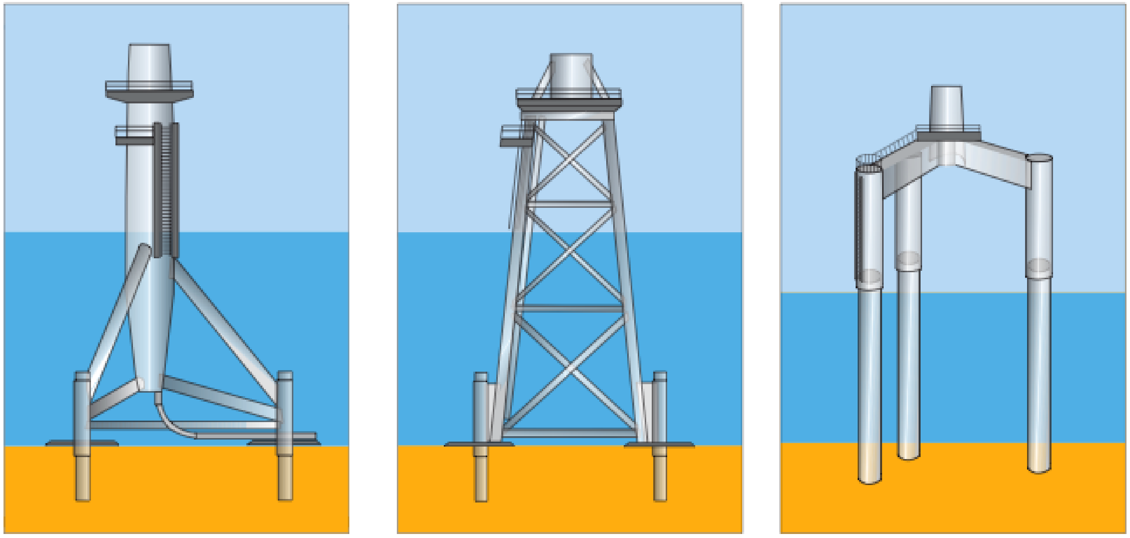
There are five popular designs for fixed-based wind turbines in shallow water. The foundations are either tubular or lattice structures. Usually the type of foundation chosen depends on the site conditions. Historically most shallow water designs have been either monopile or gravity-based foundations. However, as the wind industry moves further off the coast, other designs are being explored. They generally have a bigger footprint with broader bases and are used for water between twenty and thirty meters. The jacket, tripod, and tripile are a few examples.

Figure 2.6 Fixed-Bottom Foundations



Monopile

Gravity-based Structure (GBS)



Space Frame (Tripod)

Space Frame (Jacket)

Space Frame (Tri-pile)

Source: (European Wind Energy Association 2011)

The monopile foundation depicted in the upper left of Figure 2.6, is a simplistic lower-cost option, and therefore is generally more popular. This design can only be implemented in water less than twenty meters in depth. The monopile is a long hollow steel pole drilled and driven into the seabed up to forty meters. This structure is unusually heavy for being the less expensive option, weighing up to 500 tons with a diameter of 5.1 meters. This design is not the sturdiest option, and cannot be utilized in places consisting of a seabed of large boulders (AWS Truewind, LLC 2009).

The gravity base foundations' design, pictured in the upper right of Figure 2.6, is generally used in water less than fifteen meters in depth, but can be functional up to 29 meters in depth. This design, as do the others, has a much larger footprint than the first example, but is not driven into the seabed and can be removed completely. It also requires a massive amount of weight and potential site preparation. The foundation is made of steel and concrete and can weigh 7,000 tons. The construction of the foundation is fairly economic, but the transport and installation of it is more costly (AWS Truewind, LLC 2009).

The jacket foundation, shown in the center bottom of Figure 2.6, is very common in the oil and gas industry. It is a four sided, A-shaped lattice structure with a turbine mounted on top. The biggest benefit to this design is it can be used in waters as deep as 40 meters. Piles are driven through the feet to secure the structure. The wider cross section than the monopile strengthens this design against momentary loads. A huge benefit to this design is how light it is, weighing about 600 tons. The lattice structure is well understood in the manufacturing industry as a result of previous oil and gas industry experience. Therefore the materials and procedures are relatively readily available. It is believed that once this structure becomes slightly more popular and manufacturing reaches economies of scale, it will likely take over as the dominant choice in the fixed-bottom offshore wind industry (AWS Truewind, LLC 2009).

The tripod foundation, shown in Figure 2.6 in the lower left, builds off of the monopile design. It takes the same concept and expands the footprint, offering more stability and strength. The drawback to this design is it is time consuming and complicated to manufacture. Thus, this makes it unpopular likely leading to a limited future in the industry (AWS Truewind, LLC 2009).

The tri-pile foundation, depicted in the lower left of Figure 2.6, is fairly new to the industry and has yet to catch on in a grand scale. It is a similar concept to the monopile and tripod. However, instead of one beam drilled into the seabed, or one beam that separates into three feet, this design is three beams before it even enters the water. The wider footprint again is for increased stability and strength against loads. This foundation is designed to be functional in up to fifty meters of water and it adaptable to varying ocean floors (AWS Truewind, LLC 2009).

Assembly Options

Offshore wind turbines historically have been manufactured onshore and assembled in the ocean. This is a costly procedure requiring heavy construction vessels. This method of construction is reminiscent of the offshore oil and gas industry, which also use jack-up barges and liftboats to fit pieces together. These types of vessels are also in limited supply around the world. Some exist in Europe for the offshore wind industry, as well as in locations with oilrigs. It is possible that access to these rare vessels may be limited by the Merchant Marine Act (1920), commonly known as the Jones Act. In short, it says energy related activities in US waters must employ US vessels.

The deepwater industry in the United States is looking to solve this construction challenge. In creating floating platforms, secured by cables or mooring lines, engineers are planning on constructing and assembling the turbines and their platforms entirely onshore. This will take place most likely in shipyards, like General Dynamics: Bath Iron Works in Bath, Maine, where naval vessels are created. Shipyards not only have the space, but also use similar infrastructure in their current industry that can potentially be adapted to meet this demand. From this location the turbines will be floated and towed by a tugboat out to their resting location. This procedure is fairly time consuming, but perhaps less so in the long run than obtaining and operating the offshore construction vessels. Once in location, anchors will be dropped, or tension cables installed.

III. Wind Resource and Energy Potential in Gulf of Maine

Wind, like any other natural resource a country holds, is studied and measured by economists, scientists, and others looking to develop the resource. In 2003 the offshore wind resource of the United States was measured and published in a comprehensive report by the National Renewable Energy Laboratory (NREL). This report was followed in 2004 by an NREL report by Walt Musial and Sandy Butterfield who published an updated study on the offshore wind resource of the United States. NREL and the Department of Energy as well as others have built on this study to create a national database of the nation's offshore wind resource that defines the characteristics of the resource, which are used to quantify availability and distribution. The purpose of this database is to provide a base of information to empower the development and planning of wind-based renewable offshore energy. Wind information up to fifty nautical miles off the coast has been mapped. This includes major bays and inlets. This database is continuously being updated and improved as more accurate information becomes available.

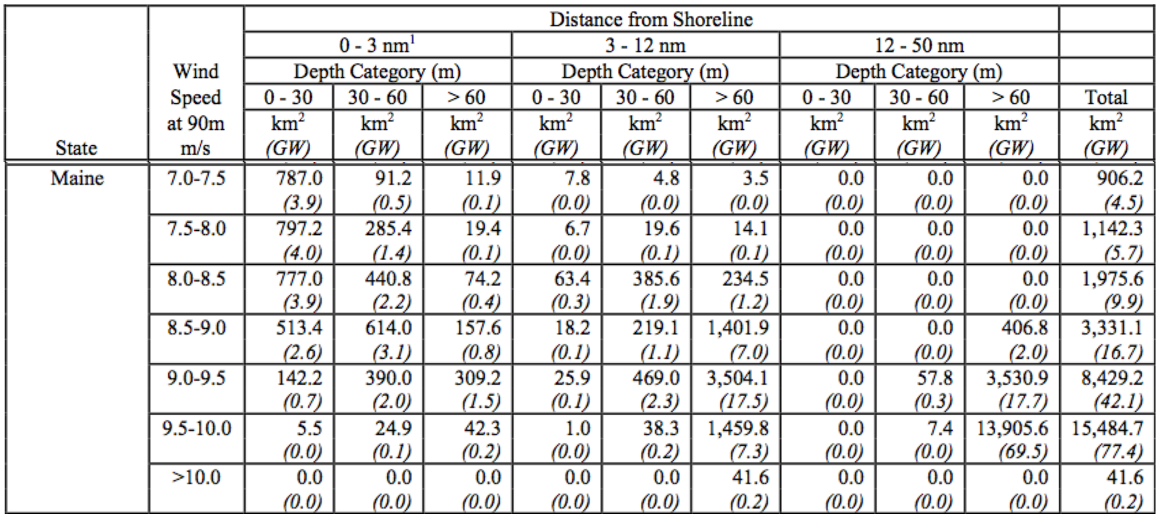
For the purpose of this thesis, we will focus exclusively on the natural offshore wind energy resource for the state of Maine. Much of this data was compiled from information from ocean buoys, weather pattern histories, marine automated systems, Coast Guard stations and lighthouses, and models. The coast of Maine is home to just under fifteen buoys owned and operated by the Northeastern Regional Association of Costal and Ocean Observing Systems, the National Oceanic and Atmospheric Administration [NOAA], the University of Maine, and Bowdoin College (NERACOOS

2012). Annual average wind speed, water depth, distance from shore, and state administrative areas are elements included in the description of the resource. Water depths came from the U.S. Department of Commerce's NOAA's Coastal Relief Model. The distance from shore also came from NOAA from their shoreline delineation. The parameter of administrative jurisdiction came from the U.S. Department of the Interior's Minerals Management Service (MMS). The database was primarily created using Geographic Information Systems (GIS) techniques, which allowed for the spatial correlation of these characteristics.

A GIS based system was chosen because of how spatially connected all of the characteristics are. If this information were presented in a bar graph or spreadsheet, the information would be too difficult to manage and understand. The GIS database is flexible allowing for future data to be added to the system such as environmental or human use considerations, for example shipping lanes, environmental exclusion areas, or navigation zones.

According to the most recent NREL report, the state of Maine has some of the best offshore wind resource in the country. More specifically, the total wind area within fifty nautical miles of the coast is 31,311 km^2. Within this area there is a total of 156.6 GW of energy in areas with mean wind speeds of over 7 m/s and at a hub height of 90m. Most of this resource is from winds between 9-10m/s average wind speeds. The largest abundance of this resource is located in waters over 60m in depth and the majority of this is between 12-50 nautical miles from shore. More specific measurements can be seen in Table 3.1 below (Musial, Butterfield and Ram 2006).

Table 3.1 Wind Speeds by Depth

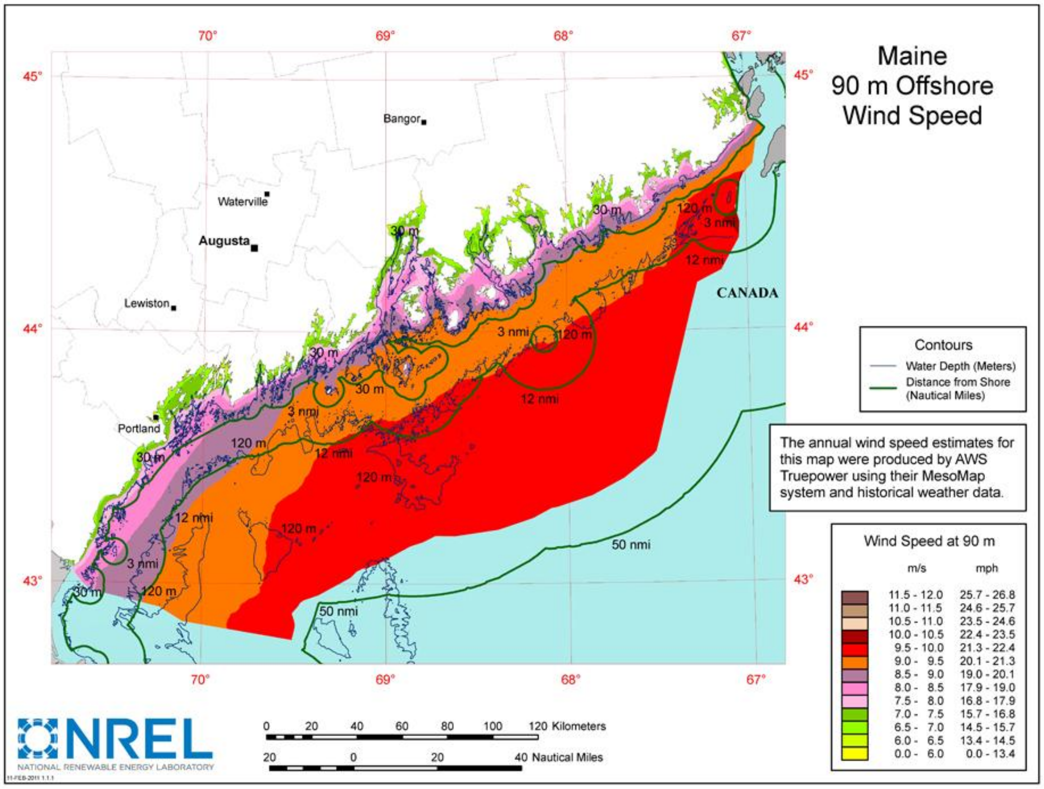


State	Wind Speed at 90m m/s	Distance from Shoreline									
		0 - 3 nm[1]			3 - 12 nm			12 - 50 nm			
		Depth Category (m)			Depth Category (m)			Depth Category (m)			
		0 - 30	30 - 60	> 60	0 - 30	30 - 60	> 60	0 - 30	30 - 60	> 60	Total
		km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*	km^2 *(GW)*
Maine	7.0-7.5	787.0 *(3.9)*	91.2 *(0.5)*	11.9 *(0.1)*	7.8 *(0.0)*	4.8 *(0.0)*	3.5 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	906.2 *(4.5)*
	7.5-8.0	797.2 *(4.0)*	285.4 *(1.4)*	19.4 *(0.1)*	6.7 *(0.0)*	19.6 *(0.1)*	14.1 *(0.1)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	1,142.3 *(5.7)*
	8.0-8.5	777.0 *(3.9)*	440.8 *(2.2)*	74.2 *(0.4)*	63.4 *(0.3)*	385.6 *(1.9)*	234.5 *(1.2)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	1,975.6 *(9.9)*
	8.5-9.0	513.4 *(2.6)*	614.0 *(3.1)*	157.6 *(0.8)*	18.2 *(0.1)*	219.1 *(1.1)*	1,401.9 *(7.0)*	0.0 *(0.0)*	0.0 *(0.0)*	406.8 *(2.0)*	3,331.1 *(16.7)*
	9.0-9.5	142.2 *(0.7)*	390.0 *(2.0)*	309.2 *(1.5)*	25.9 *(0.1)*	469.0 *(2.3)*	3,504.1 *(17.5)*	0.0 *(0.0)*	57.8 *(0.3)*	3,530.9 *(17.7)*	8,429.2 *(42.1)*
	9.5-10.0	5.5 *(0.0)*	24.9 *(0.1)*	42.3 *(0.2)*	1.0 *(0.0)*	38.3 *(0.2)*	1,459.8 *(7.3)*	0.0 *(0.0)*	7.4 *(0.0)*	13,905.6 *(69.5)*	15,484.7 *(77.4)*
	>10.0	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	41.6 *(0.2)*	0.0 *(0.0)*	0.0 *(0.0)*	0.0 *(0.0)*	41.6 *(0.2)*

Source: (Schwartz, et al. 2010)

This information was then converted into map form for a more comprehensive visual of the wind speeds. The following map is of the Gulf of Maine. What is important to retain from this map is that the red area is the strongest winds off the coast and is located in the deepest waters.

Figure 3.1 State of Maine Offshore Wind Speeds



The annual wind speed estimates for this map were produced by AWS Truepower using their MesoMap system and historical weather data.

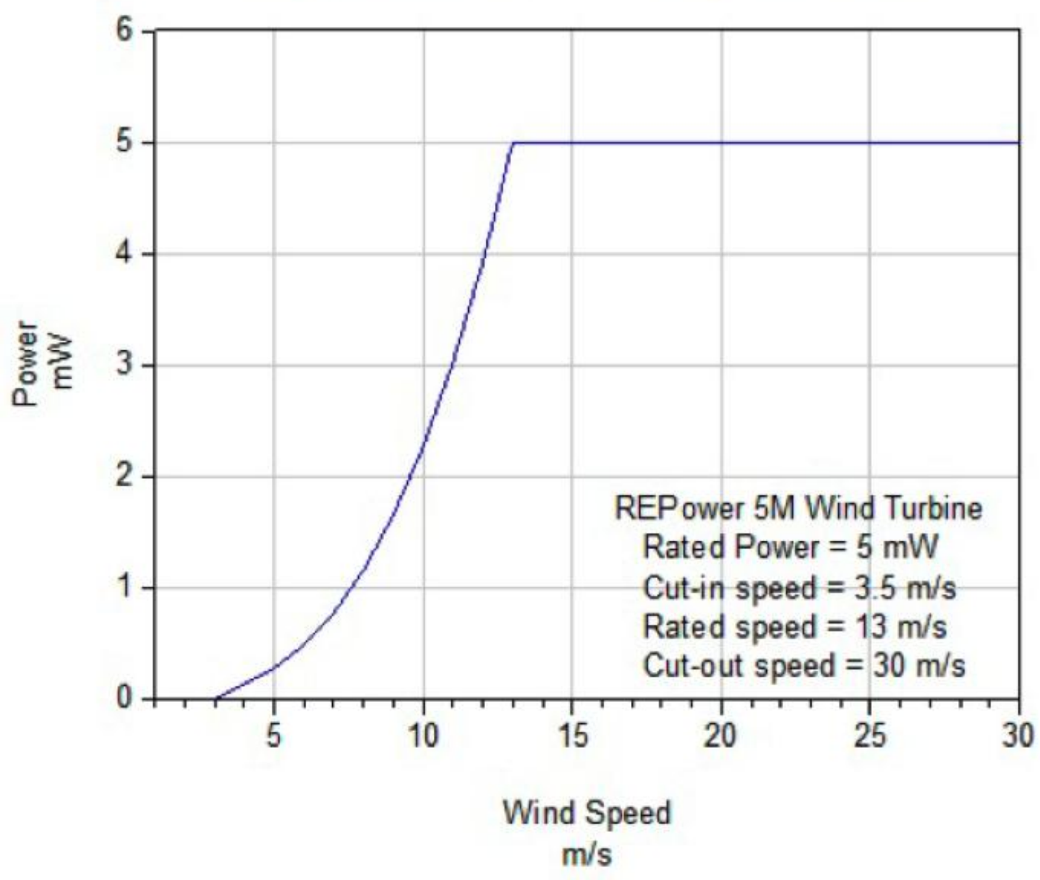
Source: (Musial, Butterfield and Ram 2006)

Power Curves

When looking at wind turbines and expected output, one must distinguish between power and energy. Power is the rate at which work is performed, whereas energy is the amount of power consumed over a period of time. Factors including wind speed, air density and the area through which the wind is blowing all play a role when calculating the power of the wind. Power is measured in kilowatts (kW), megawatts (MW), and gigawatts (GW). Electricity is measured in kilowatt-hours (kWh), megawatt-hours (MWh), and gigawatt-hours (GWh).

Power curves for wind turbines vary slightly, but more or less follow the same general paths. A cut-in speed is the speed at which the wind must blow in order for the turbine to begin producing power. Turbines are rated at specific output levels known as their nameplate capacity or rated power. A 5MW turbine at its maximum will produce 5MW of power. The rated speed is the speed that the wind must be blowing for the turbine to reach this capacity. The cutout speed is the speed of the wind that is too fast for the design of the turbine and is the speed beyond which the turbine pitches its blades to shutdown and avoid damage.

Figure 3.2 REPower 5MW Wind Turbine Power Curve



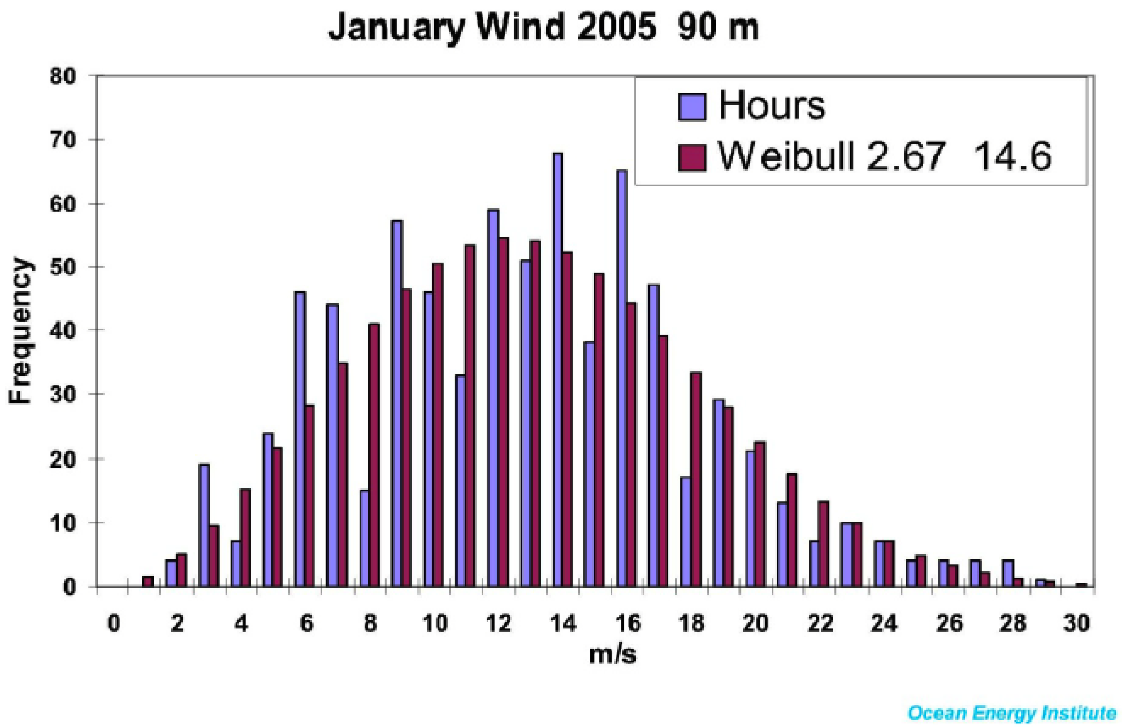
Source: (G. L. Hunt 2009)

Figure 3.2 is a power curve of a specific wind turbine produced by REPower. All turbines have their own power curves. This one is used as a specific example. It was chosen because it is for a 5MW turbine and most current turbines in use onshore are around 2.5MWs. The scale of this turbine is more like what is being considered for the Gulf of Maine.

When looking at the power curve of the REPower 5MW Turbine with 63 m blades, one can quickly see these aspects of the technology. The cut-in speed is where the line starts, here at 3.5 m/s. The rated power is 5MW, which makes the rated speed 13 m/s. The power curve then flat-lines until it reaches the turbine's cutout speed of 30 m/s.

One can begin the see the importance of proper siting and areal organization so that the technology can maximize the energy produced from the natural resource. Information was analyzed from the Mount Dessert Rock metrological tower, specifically for the month of January in 2005, to give an example of how the wind resource and the turbine's power curve interact to produce expected energy output. A graph of the wind speeds is provided in Figure 3.3.

Figure 3.3 Weibull Distribution for January 2005 Hourly Wind Speeds Mt. Dessert Rock



Source: (George Hart n.d.)

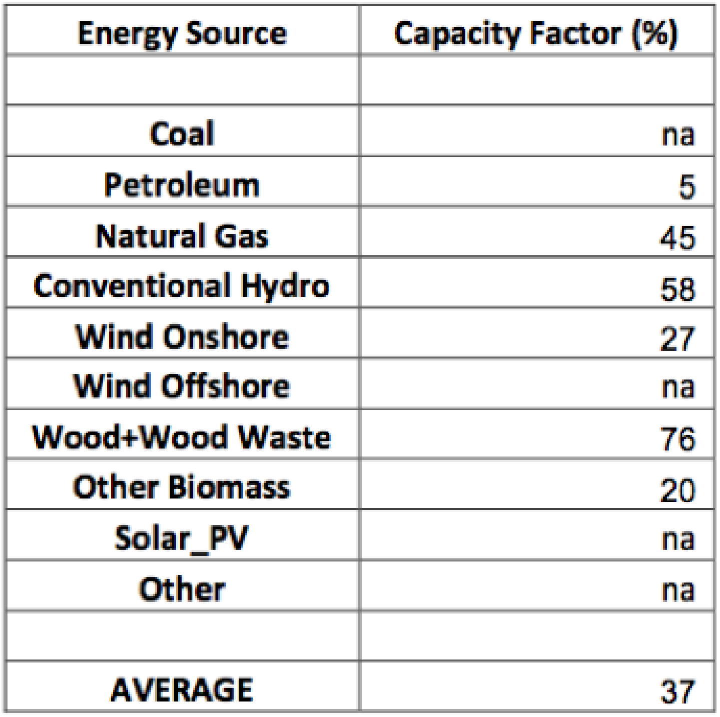
The blue bars are the observed data, and the purple bars are the Weibull distribution through the observed data. This distribution of wind speeds becomes important when combining it with the power curve to get expected energy output. Year over year, the data varies some, but eventually an average is apparent and can be used to calculate expected output. For example, the distribution above shows the wind speeds at this location are most frequently between 11 and 14 m/s. This means the turbine will be producing or nearly producing its rated power for the majority of the time. This graph also shows the wind is rarely lower than the cut-in speed, meaning the turbine will be producing some power nearly all of the time. And, it is almost never blowing faster than the cutout speed of 30 m/s, again meaning the turbine is almost always producing energy.

Capacity Factor

Capacity factors are the ratio of actual output of power to the theoretical potential maximum output if the turbine(s) were running full time at their rated power. Capacity factors can be computed for a single turbine, a farm, or a whole industry. Every type of energy generation has capacity factors. These factors are especially important for offshore wind because of the typical improvement from onshore wind capacity factors. Capacity factors across the board vary greatly depending on technology, resource intermittency, role played in the grid, etc. Intermittent technologies such as wind power are most dependent on geographic location and the actual power of the resource. However, turbine design also plays a role. Most of the research into capacity factors at this point has been focused on how to increase them with improvements in technology.

The state of Maine varies from other states in terms of capacity factors. The following table, Table 3.2, compares Maine’s average capacity factors across energy types. Resource, technology, and purpose contribute to the variation between types of power.

Table 3.2 Maine Average Capacity Factors 2007



Energy Source	Capacity Factor (%)
Coal	na
Petroleum	5
Natural Gas	45
Conventional Hydro	58
Wind Onshore	27
Wind Offshore	na
Wood+Wood Waste	76
Other Biomass	20
Solar_PV	na
Other	na
AVERAGE	37

Source: (G. L. Hunt 2010)

It is also worth noting that capacity factor and efficiency are two entirely different measurements. Efficiency refers to useful output in relation to input effort. Efficiency accounts more for specific technological designs than it does for the industry as a whole. Efficiencies account for losses. The loss of efficiency happens when some of the resource is lost in thermal, mechanical, and electrical inefficiencies. Efficiency measurements are particularly important to the offshore wind industry because wind generally has a much lower capacity factor, but much higher efficiency than typical fossil fuels (Renewable Energy Research Laboratory n.d.).

Full Load Hours

A full load hour is an hour where a wind turbine produces energy at full capacity. Usually full load hours are presented in an annual number which is the time it takes a turbine to yield its annual production if it ran at its fully rated capacity during all of these hours. Capacity factors are used to calculate full load hours. Full load hours are then used in calculating the average costs per kWh as a measurement of electricity output.

If we are calculating full load hours on an annual basis in terms of hours, there are 24hr/day x 365.25 days/yr = 8,766 hrs/yr. If the wind farm is operating at an annual capacity factor of 27% for 8,766 hrs/yr (.27 x 8,766 = 2366.82kWh) its full load hours are 2366.82 hours per year.

Expected Output

All of these components can be combined to estimate energy output for a turbine, or a farm of turbines. The following table is a step-by-step series of calculations for the total expected energy output in kWhs from a hypothetical REpower 5MW turbine with an 80m-hub height on Mt. Desert Rock in January of 2005 based on data collected from a metrological tower and its readings for that month.

Table 3.3 REPower 5 MW Turbine Expected Output for Jan. 2005

m/s	Probability	Hours	V	Power (kW)	Energy (kWh)
0-3	0.014518				
3	0.016516	12	3.5	98	1199
4	0.024564	18	4.5	207	3790
5	0.033278	25	5.5	379	9375
6	0.042175	31	6.5	625	19613
7	0.050745	38	7.5	960	36251
8	0.058473	44	8.5	1398	60808
9	0.064883	48	9.5	1951	94199
10	0.069573	52	10.5	2635	136381
11	0.072258	54	11.5	3462	186090
12	0.072796	54	12.5	4445	240759
13	0.071205	53	13.5	5000	264884
14	0.067660	50	14.5	5000	251696
15	0.062471	46	15.5	5000	232393
16	0.056050	42	16.5	5000	208505
17	0.048861	36	17.5	5000	181765
18	0.041377	31	18.5	5000	153923
19	0.034027	25	19.5	5000	126580
20	0.027163	20	20.5	5000	101046
21	0.021040	16	21.5	5000	78267
22	0.015805	12	22.5	5000	58794
23	0.011508	9	23.5	5000	42811
24	0.008118	6	24.5	5000	30200
25	0.005545	4	25.5	5000	20628
26	0.003665	3	26.5	5000	13634
27	0.002343	2	27.5	5000	8715
28	0.001447	1	28.5	5000	5384
29	0.000864	1	29.5	5000	3213
30	0.000498	0	30.5	5000	1851
31+	0.000572				
SUM	**1.00000**	**733**			**2,572,757**

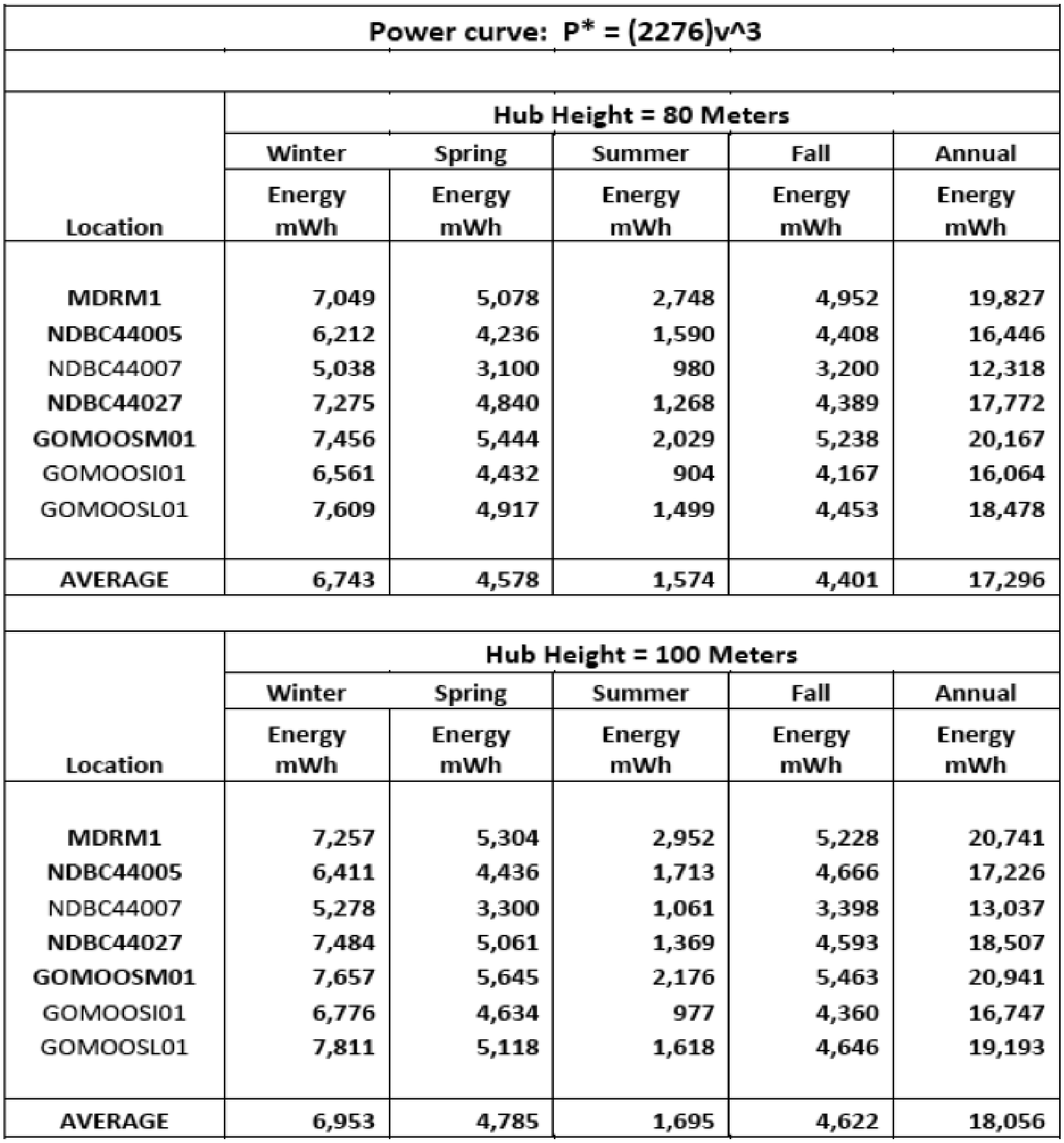
Source: Calculations by Author

This table was created as a combination of the REPower 5MW power curve and the Weibull wind distribution of January 2005, Figures 3.2 and 3.3, to get the expected output in kWhs for that month in that year with that turbine. This was done as an exercise to show how this can be done for a variety of turbines over the course of many months and years. The REPower 5MW turbine has a cut-in speed of 3.5 meters per second (m/s) and a cutout speed of 30 m/s. Energy will only be produced within this range, but there is a small probability the wind will blow as a speed that falls outside this. Therefore, this chart ranges from zero to thirty-one and over.

The probability column was calculated using a Weibull function and is the probability, based on the data graphed in Figure 3.3, that the wind will blow at a specific speed within that timeframe. In the next column, this was converted to how many hours in a month the wind would blow at that speed. The velocity column (V) exists because velocity is needed to calculate power. Since the probabilities were for a range from 3.0 to 3.9 m/s for example, a midpoint of 3.5 m/s was used for the velocity of that bar. The calculation for power used the equation $P=1/2\rho Av^3$. In this equation, P is power, rho is air density, A is the cross-sectional area the wind is blowing through, and v is velocity (G. L. Hunt 2009). A constant of 2,276 is created from $1/2\rho A$, and v^3 changes based on the velocities from the previous column. This was converted to kilowatts. Once the table reaches the row for 13 m/s however, power flatlines at 5,000kWs because this is the rated power of the turbine. The energy column takes the power and multiplies it by the hours. This is summed for a total of 2,572,757kWhs of energy for the month of January in 2005 from a hypothetical turbine with an 80m-hub height.

The following table, Table 3.4, combines about ten years of wind data at the various locations off the coast of Maine with the power curve for the REpower 5MW Turbine. This table, done by Gary Hunt also uses two different potential hub heights.

Table 3.4 REPower 5MW Wind Turbine Energy Outputs



Power curve: P* = (2276)v^3

Location	Hub Height = 80 Meters				
	Winter	Spring	Summer	Fall	Annual
	Energy mWh	Energy mWh	Energy mWh	Energy mWh	Energy mWh
MDRM1	7,049	5,078	2,748	4,952	19,827
NDBC44005	6,212	4,236	1,590	4,408	16,446
NDBC44007	5,038	3,100	980	3,200	12,318
NDBC44027	7,275	4,840	1,268	4,389	17,772
GOMOOSM01	7,456	5,444	2,029	5,238	20,167
GOMOOSI01	6,561	4,432	904	4,167	16,064
GOMOOSL01	7,609	4,917	1,499	4,453	18,478
AVERAGE	6,743	4,578	1,574	4,401	17,296

Location	Hub Height = 100 Meters				
	Winter	Spring	Summer	Fall	Annual
	Energy mWh	Energy mWh	Energy mWh	Energy mWh	Energy mWh
MDRM1	7,257	5,304	2,952	5,228	20,741
NDBC44005	6,411	4,436	1,713	4,666	17,226
NDBC44007	5,278	3,300	1,061	3,398	13,037
NDBC44027	7,484	5,061	1,369	4,593	18,507
GOMOOSM01	7,657	5,645	2,176	5,463	20,941
GOMOOSI01	6,776	4,634	977	4,360	16,747
GOMOOSL01	7,811	5,118	1,618	4,646	19,193
AVERAGE	6,953	4,785	1,695	4,622	18,056

The location column references specific buoys, either Gulf of Maine or NOAA, or a NOAA CMAN, off the coast of Maine that collect wind data. These locations can be found at http://neracoos.org/realtime_map. MDRM1 refers to the data collected on Mount Desert Rock is a NOAA CMAN.

Source: (G. L. Hunt 2009)

For the Mount Desert Rock location, annual expected energy output is 19,827MWhs. This number is only for one turbine. This number will become important in subsequent chapters for calculating the costs associated with offshore wind.

IV. Private Costs

As is true for all estimates regarding deepwater offshore wind electricity generation, predictions are based on other similar industries. Deepwater offshore wind estimates for private costs originate from data in the fixed-bottom offshore industry, particularly in Europe where deployment is flourishing. This is similar to how offshore wind estimates ten years ago were adapted from numbers in the onshore wind industry. The burden for the cost of offshore wind energy mainly falls in capital costs. Private costs include capital costs and operation and maintenance costs.

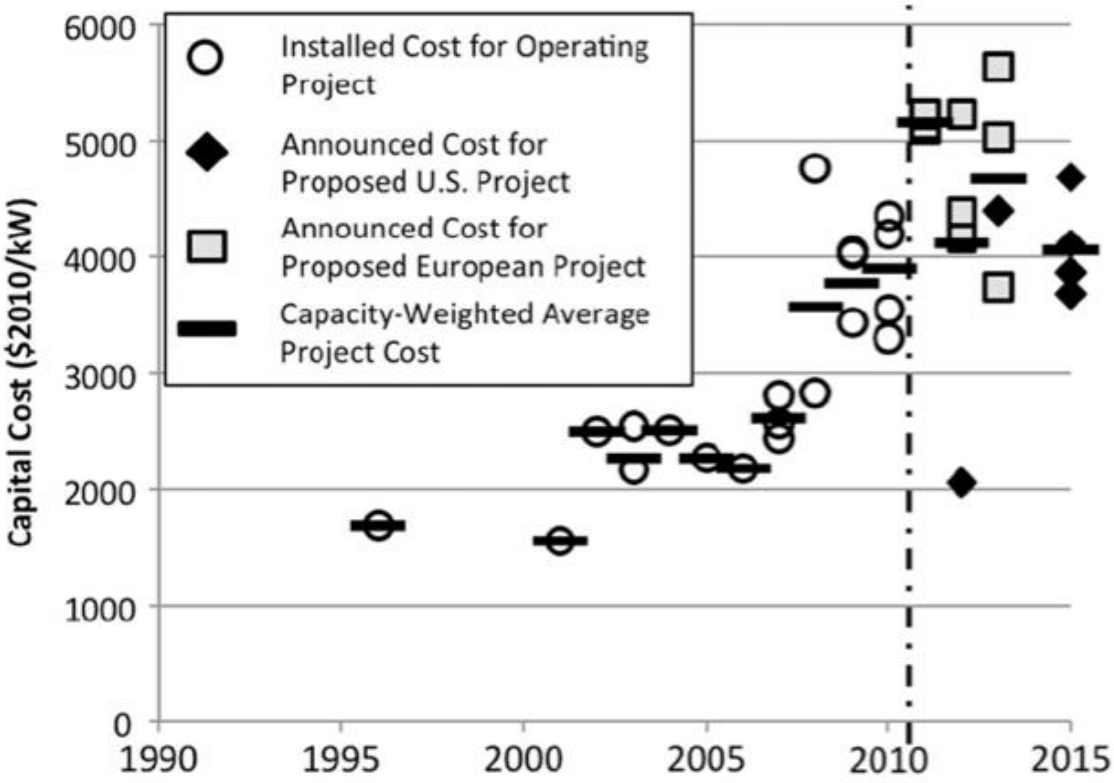
To put all types of energy on the same playing field, economists levelize the cost of energy. To calculate this, the estimated annual costs are divided by the expected annual quantity of electricity and presented in cents or dollars per kilowatt-hour. Capital costs, operation and maintenance costs, and fuel costs are included in the estimated annual costs. The expected annual quantity depends on the power of the wind resource and the turbine characteristics using capacity factors. The levelized private cost of energy (LCOE), as estimated in this thesis, takes into account total project capital costs, financing and depreciation (capital recovery) rates, operation and maintenance costs, any fuel costs, and the expected full load hours. The levelized cost of energy for offshore wind is expected to decrease over time as the industry matures and learning curve effects are seen. For the scope of this thesis, LCOE is simplified and the key aspects highlighted. Tax effects are omitted, but all values are stated in constant 2010$ thereby eliminating the influence of inflation.

Capital Costs

It is well known that capital costs (CAPEX) in the offshore wind industry are relatively high at the current time. This can be seen when looking at comparisons in the wind industry in Europe (Levitt, et al. 2011). CAPEX includes what goes into buying and building wind farms and results in benefits lasting longer than one year (Levitt, et al. 2011).

When looking at recent years in the wind industry, capital costs have not decreased as they had been predicted to do. Instead, they have increased from 1990 to 2010 and costs are predicted to continue increasing.

Figure 4.1 Capital Costs for Installed Projects and Released Capital Costs for to be Installed Projects



This is a figure depicting CAPEX/kW for European and US offshore projects. Points to the right of the dotted line are planned projects as of 2010, as this report was released in 2011. CAPEX shows a marked increase from 2007 through 2010.

Source: (Levitt, et al. 2011)

Figure 4.1 only represents offshore projects. All currently installed and operating projects are European, as the United States does not have any offshore wind yet. However, there are some proposed projects in the US that have released their estimates in the media and reports, which have been added, based on their reported years of deployment.

Two possible explanations for this rising CAPEX trend exist: reasons exclusively related to the wind industry, and reasons resulting from a larger macroeconomic view. This thesis is not meant to speculate, but rather it is important to point out explanations for why CAPEX could be increasing, as it is a factor in calculating costs. The increase in capital costs over time cannot be explained by one contributor, but instead is a combination of many factors.

Focusing on the microeconomic perspective of the wind industry, the increase in CAPEX is partially attributable to basic supply and demand. There has been a push in recent years to develop capacity aggressively, but currently as it stands, there is a limit to what the supply chain can produce. This increase in demand is both attributed to the booming onshore industry as well as the political push to develop all forms of renewable energy, moving nations away from harmful fossil fuels and towards energy security. As basic economics explains, when there is an increased demand and the increase in supply does not match, there will be an increase in the inflation-adjusted real price. This is especially true in the offshore industry in regards to ports and vessels. There is already a shortage of these, and the wind industry often has to compete with the oil and gas industry for use of these ports and vessels (Levitt, et al. 2011).

The macroeconomic side of capital costs for wind energy development refers to aspects out of the control of the industry (Levitt, et al. 2011). In recent years, some of these factors have included the economic recession, currency movements, labor rates, and commodity prices. Clearly, if the price of the building materials increases, the price of the final product will increase as well. There have been record high fossil fuel prices, and although this is an incentive to build more wind energy, it also makes the construction of that new energy producing device more costly on an inflation-adjusted basis, creating a vicious cycle. The machines and vehicles needed to build and transport what goes into a wind farm rely on fossil fuels, and the price of the project will increase if these prices increase.

Turbines are single-handedly the largest cost for developing a wind farm. Turbine prices are dependent on commodity and other input prices. For example, steel is an important building material in turbines and has significantly increased in price since 1990. However, input prices do not account for the full reason the price of turbines has increased over time. Recent wind farms have also tried to correct the errors and shortcomings of earlier farms. This requires new and more advanced technology Therefore, the early 2000 costs for wind farms did not appropriately reflect the real cost of the wind farm as they did not make back all that was expected to and had to reinvest to fix what went unpredicted.

Foundations are the second most costly part of an offshore wind farm. They are affected by the same factors as the turbines meaning they are dependent on commodity and other input prices. In recent years, with the invention of a lattice style fixed-bottom foundation, the capital costs involved with foundations has decreased for farms that chose this technology. In regards to deepwater wind, the costs of fixed-foundations do not apply as there are no fixed-foundations. However, there are costs for the floating platform foundations and other components associated with a deepwater farm. Because of this change in variables and the lack of existing deepwater farms, there are limited data on different on which to base a difference in cost. Due to the fact that these turbines will be floating and will be fully constructed on land, developers hope that the costs will be significantly lower than for traditional fixed-bottom designs. Much of the budget that goes into a turbine is the crane time and jack-up barges that are required to erect the turbines. Floating technology will attempt to avoid much of this cost.

Historically speaking, the farther out to sea a wind farm is, the more costly the capital investment has been. This is due to the increase in materials needed to reach the bottom and to bring the generated electricity back to shore, i.e. cables and the foundations. For deepwater wind energy, the floating platform design allows for potential savings in either materials that would be used in the foundation, fabrication of the structures, or deployment methods. These potential cost savings could be transferred to the costs involved in the increased infrastructure needed to bring the energy to shore, transporting the turbine to its location, and mooring line and anchoring costs that currently are not as expensive or do not exist at all when working in shallow water. Then again, the hope is that the larger quantities of energy produced farther offshore due to the stronger wind resource will counteract these added expenses.

To compare costs for farms of different sizes, economists break the cost down into dollars per kilowatt. Again, all the data available to analyze this is from fixed-bottom offshore wind or from onshore wind farms. The US Energy Information Administration estimates offshore wind costs of $5975/kW whereas NREL's 2010 capital costs are reported at $4250/kW (G. Hunt 2011). A University of Delaware study found running commercial-scale farms have ranged between $1500 and $4750/kW. Estimated costs on contracted projects in the years after 2010 range from $3500 to $5750 (Figure 4.1). This estimate is a smaller range but increasing overall. This thesis will use an estimate of $6,000. This will provide a conservative estimate that compensates for the discrepancies in estimates of capital costs for offshore wind, will account for the uncontrollable macroeconomic factors, and will rectify the assumption of an increasing capital cost the farther from shore a farm is.

The most important factor when analyzing capital costs is learning curve effects. Without including this variable for the wind industry, high capital costs make projects not economically viable and look as if they could never become competitive with alternative sources of energy. Learning curve effects refer to the learning-by-doing principal and result in a decrease in capital costs over time due to increased learning in the industry and increased efficiency as the cumulative number of units are developed and built out. Studies have been conducted on the effect of learning in the renewable energies industry and have recognized the prevalence and importance of them (Levitt, et al. 2011). Economists measure learning curve effects based on doublings of cumulative installed capacity to average reductions in cost.

A learning rate of 10 percent is common in the wind industry (G. Hunt 2010; Greenacre, Gross and Heptonstall 2010). After the first doubling of capacity, for example 50 MW to 100 MW, the capital costs will be 90 percent of what they were initially ($(0.90^1) \cdot q = 0.90 \cdot q$, where q is the initial capital cost). After the next doubling costs will be 81 percent of what they were initially ($q \cdot (.90^2) = 0.81 \cdot q$), and so on. Conservatively estimating the initial capital costs at $6000, we can include the learning rate per doubling decrease in cost.

Table 4.1 Learning Curve Effects on CAPEX

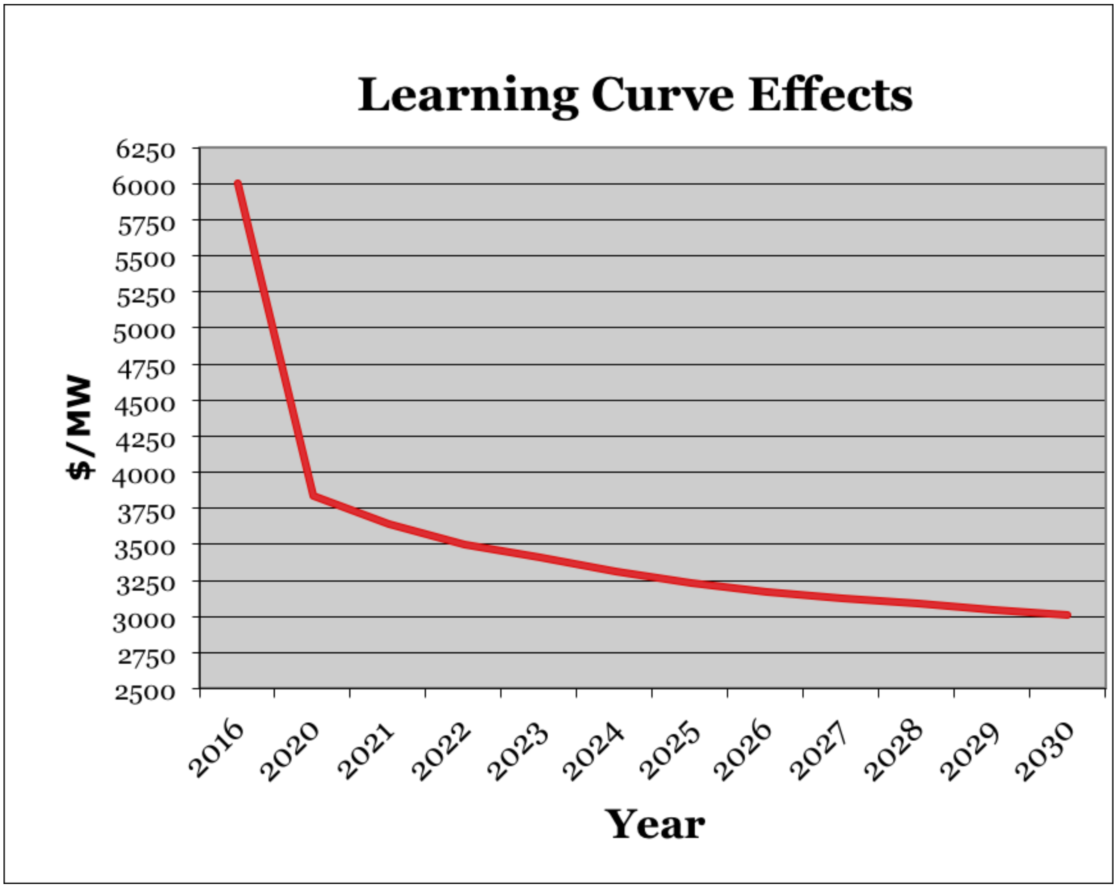
Installed Capacity (MW)	Doublings	CAPEX Factor	CAPEX Estimate with $6000 Initial ($)
50	0	1	6000.00
100	1.00	0.90	5400.00
200	2.00	0.81	4860.00
300	2.50	0.77	4610.60
400	3.00	0.73	4374.00
500	3.25	0.71	4260.29
600	3.50	0.69	4149.54
700	3.75	0.67	4041.67
800	4.00	0.66	3936.60
900	4.13	0.65	3885.09
1000	4.25	0.64	3834.26
1100	4.38	0.63	3784.10
1200	4.50	0.62	3734.59
1300	4.63	0.61	3685.72
1400	4.75	0.61	3637.50
1500	4.88	0.60	3589.91
1600	5.00	0.59	3542.94
…	…	…	…
3200	6.00	0.53	3188.65
5000	6.56	0.50	3005.16
6400	7.00	0.48	2869.78

Source: Created by author

In just eight doublings of the industry, the CAPEX estimate is less than half of what it started at. Before this information is relevant for CAPEX the learning rate must be translated into real world time by looking at the temporal build-out profile. The wind project for deepwater offshore wind in the state of Maine with research done by the DeepCwind Consortium provides a timeline for estimated MWs deployed until 2030 (DeepCwind Consortium 2012). The timeline is vague due to the dependence on the not yet officially contracted developer, and this offshore wind plan has been revised since its initial release date with revisions yet to be published. However, the wind plan does provide a general ideal for the goal of deepwater wind electricity generation for the state. From 2011-2015 there will be one 3-5MW turbine. This will quintuple to a 25MW stepping-stone farm by 2016. By 2020, this will increase to a full-scale commercial farm of 1,000MW, with a goal of 5,000MW by 2030.

Applying DeepCwind's timeline (DeepCwind Consortium 2012), 25 MWs will be installed by 2016. Installations prior to this will not be commercial scale and therefore will not be appropriately indicative of costs due partially to economies of scale. Conservatively estimating the initial CAPEX at $6000, by the year 2020, there will be 1000MW with capital costs down to $3834.26. When installed capacity reaches 1500MW, CAPEX will be down to $3589.91. This is still expensive, but is a huge improvement from the initial $6000. Finally when the 5GW or 5,000MW goal is reached by 2030, the dollars per kW will have dropped to $3005.16.

Figure 4.2 Learning Curve Effects



The graph begins at year 2016 and skips to 2020. Regardless of this, there still remains a significant and drastic drop in costs from 2016 to 2030.

Source: Created by author

Figure 4.2 displays the learning curve effects on CAPEX of a projected fourteen-year linear increase in development and build out of 5,000 MW of commercial deepwater wind farms through 2030 in the Gulf of Maine. Figure 4.2 exists as a visual representation of learning curve effects and how significantly they can decrease costs over a given period of time. To create this figure, the benchmarks of 50 MW, 1,000MWs by 2020 and 5,000MWs by 2030 were used. The 4,000MW increase in the industry between 2020 and 2030 was taken to be a linear increase of 400MWs per year in order to permit the application of the data displayed in Table 4.1. It can be assumed that the industry will reach a maximum output of production at some point. The maximum used here was 400MWs a year. However, these learning curve effects will only occur as the industry is developed. Therefore to decrease costs, more development, especially in the United States, needs to occur.

Levelized Cost of Energy

Learning curve effects are what will make deepwater offshore wind competitive in the long run, but to look at the costs with the same common denominator as other types of energy generation a method called levelizing the cost of energy is used. To annualize CAPEX (C) the equation $C = (r + d)\cdot q$ is used. The variable r is the rate of return, or the weighted average cost of capital. The variable d is depreciation, or also referred to as capital recapture. Lastly, q, the CAPEX variable developed above, is the estimate for CAPEX, which falls over time due to learning curve effects.

Depreciation is the loss of value of an item over its lifespan. It is assumed that a turbine will have a lifespan of twenty years. At the end of its life, it is assumed there is no value left in the turbine or that scrap value is equal to decommissioning costs. The value of the turbine slowly decreases every year until it reaches twenty years and is no longer worth anything. It is also assumed that turbines for this future deepwater offshore industry have equal construction time to offshore turbines currently. Depreciation is calibrated to recapture the loss of value over the twenty years of the turbine's assumed useful life. A turbine with a twenty-year lifespan is assumed to lose five percent of its value every year. Therefore the variable d in this equation is 0.05.

The variable r is a little more complicated. As the weighted average cost of capital, it uses the equation $r = [(w_d \cdot r_d) + (w_E \cdot r_E)]$ where r_d is the real interest rate on debt, r_E is the real rate of return on equity, w_d is the share of the financing that is debt and w_e is the share of the financing that is equity. By definition, $w_d + w_E = 1$. Studies have been done on this weighted average cost of capital and have found 10 percent to be a fair average for wind projects (Greenacre, Gross and Heptonstall 2010). Therefore, $r = 0.10$. As throughout this thesis, a simplification is made in ignoring tax code effects in the weighted average cost of capital.

At this point, the annualized cost of capital can be calculated.

$C = (r + d) \cdot q = (0.10 + 0.05) \cdot \$6{,}000$ per kW

$C = \$900$/kW per year

This is where expected output from the previous chapter comes into play. Using a combination of papers with different capacity factors including Great Expectations from the UK Energy Research Centre (Greenacre, Gross and Heptonstall 2010), Hunt’s Wind Resource Paper (G. L. Hunt 2009), Anthony Viselli’s calculations (Dagher, Hunt and Viselli 2011), and Offshore Wind in the Gulf of Maine by Jim Mays (Mayes 2011), an average capacity factor of 45 percent is used to calculated the expected output. Noting that there are 8,766 hours in a year, the aforementioned capacity factor gives an expected output of an offshore turbine as 8,766 · 0.45 = 3,944.7 full load hours per year. The capital component of the levelized cost of energy is calculated by dividing the annualized capital cost by this full load hour measure of expected output:

LCOE = $\underline{\$900/\text{kW per year}}$ / 3,944.7 hours per year = $0.23 / kWh

In addition to capital costs, there are operating and maintenance (O&M) expenditures. These numbers vary greatly due to a lack of reported information. OPEX includes operating and maintenance costs, administrative costs, rent, interconnection infrastructure, insurance, taxes, royalties, and rights of way. The best data on operating expenditures is from the first group of UK projects. O&M expenditures for these projects ranged from $12 to $36 per MWh with an overall capacity-weighted average of $19/MWh (Levitt, et al. 2011). Taking this average and converting it to a kWh basis yields $19/1000 = $0.019/ kWh.

Adding this to the capital component of the LCOE gives

$0.23 + $0.019 = $0.25/kWh.

This method of levelizing the cost of energy can be integrated with the learning effects on capital costs developed earlier and then be applied over the span of years previously analyzed.

Table 4.2 LCOE by Year for Offshore Wind

Year	**Installed Capacity (MW)**	**Doublings**	**CAPEX Factor**	**CAPEX Estimate with $6000 Initial ($/kW)**	**Annualized Cost of Capital with Learning Curves ($/kW)**	**Annualized Capital Cost with Learning Curves ($/kWh)**
2016	25-50	0.00	0	6000.00	900.00	**0.2282**
2020	1000	4.25	0.64	3834.26	575.14	**0.1458**
2021	1400	4.75	0.61	3637.50	545.63	0.1383
2022	1800	5.13	0.58	3496.59	524.49	0.1330
2023	2200	5.38	0.57	3405.69	510.85	0.1295
2024	2600	5.65	0.55	3307.73	496.16	0.1258
2025	3000	5.88	0.54	3230.92	484.64	**0.1229**
2026	3400	6.06	0.53	3167.72	475.16	0.1205
2027	3800	6.19	0.52	3126.27	468.94	0.1189
2028	4200	6.31	0.51	3085.37	462.81	0.1173
2029	4600	6.44	0.51	3045.00	456.75	0.1158
2030	5000	6.56	0.50	3005.16	450.77	**0.1143**

Source: Created by author

This table applies the DeepCwind Consortium’s annualized wind plan to the private cost analysis. The installed capacity, doublings, CAPEX factor, and CAPEX estimate are the same as developed in Table 4.1. This number then was annualized, like above, for all the years. It then was converted from dollars per kW to dollars per kWh. To do this the previous column was divided by 3,944.7, or the expected annual per kW of capacity output with a 45 percent capacity factor.

The only variables not included in this chart are the O&M costs. For offshore deepwater wind, the fuel costs are zero, as the fuel source, or wind, is free. There are some costs for fuel that go into the creation and transporting of the turbines, but these are included in CAPEX. The following table is a continuation of the annualized capital costs with learning curves in dollars per kWh with O&M costs added. O&M costs were compiled from offshore UK projects that found a capacity-weighted average of $0.019kWh (Levitt, et al. 2011). The final levelized cost of energy including learning curves and operation and maintenance costs can be seen in Table 4.3.

Table 4.3 LCOE for Offshore Wind including O&M

Year	**Annualized Cost of Capital with Learning Curves ($/kWh)**	**LCOE ($/kWh)**
2016	0.2282	**0.2472**
2020	0.1458	**0.1648**
2021	0.1383	0.1573
2022	0.1330	0.1520
2023	0.1295	0.1485
2024	0.1258	0.1448
2025	0.1229	**0.1419**
2026	0.1205	0.1395
2027	0.1189	0.1379
2028	0.1173	0.1363
2029	0.1158	0.1348
2030	0.1143	**0.1333**

Source: Created by author

The bottom line is that deepwater offshore wind is relatively expensive. By the year 2030 it is projected to be around $0.13 per kWh. The question becomes is it worth it? Can the United States and Maine continue on the path they are on now? To address some of these questions and put offshore wind into perspective, natural gas was also analyzed. The choice of a comparative analysis with combined cycle gas turbine (CCGT) technology is that its use has expanded significantly in New England over the last decade and it is the technology that often sets regional electricity prices (ISO New England Inc. 2012).

Natural Gas

Natural gas, a fossil fuel like coal or oil, has risen recently to become a cheap and cleaner alternative to coal and petroleum-based products. Climate change, due to greenhouse gas emissions, is a pressing issue in today's world, and natural gas, though in some cases not as dirty as other fossil fuels, still emits carbon. Current trends confirm the fuel's rising prominence, which could be worrisome for clean developments such as offshore wind in Maine and for the planet.

The International Energy Agency (IEA) released a special preliminary report in June 2011 entitled "Are We Entering the Golden Age of Gas?" depicting the favorable circumstances for natural gas use in the coming years. The report projects that natural gas could overtake coal as a power source by 2030, and jump from 21 to 25 percent of the global energy mix by 2035 (International Energy Agency 2011). Supplies of gas are also growing rapidly. BP's Statistical Review of World Energy (BP 2011) estimates supplies grew by 22.6 percent last year, and by 58.0 percent over the past five years. This increase in accessibility is driven by technological improvements in extracting unconventional gas (such as shale gas, now accessed by hydraulic fracturing or "fracking") and transporting liquefied natural gas (LNG). Combined with the drop in global energy demand in 2008 and 2009, the world has seen an excess supply in the natural gas market, stimulating increased investment in natural gas power generation now and in the future.

Given these gas industry dynamics, some have suggested Maine should redirect its investments in deepwater offshore wind power to further develop existing natural gas technologies and infrastructure. With its current low price and relative abundance, it makes sense to shift electricity production, transportation, and residential heating to the newly surging fuel source, while still recognizing the costs of natural gas when weighing Maine’s energy future. Simultaneously, nations need to understand wind and gas are not mutually exclusive energies; they can be used in conjunction to provide a more secure and greener energy future.

With all its obvious benefits, it is easy to discount some of natural gas’ more concerning characteristics. To integrate natural gas more greatly into the energy portfolio, we must come to terms with three undeniable facts regarding this fossil fuel: it emits carbon dioxide and other greenhouse gases, it undergoes severe price swings, and it exists in finite supply.

According to the Environmental Protection Agency, in 2009 greenhouse gas (GHG) emissions were 6,633.2 Tg or million metric tons of carbon dioxide equivalent in the United States (Environmental Protection Agency 2011). Natural gas accounted for nearly a quarter of carbon dioxide emissions, with carbon dioxide making up the vast majority of greenhouse gas emissions. Though natural gas produces less GHG emissions in total than coal, it has a higher concentration of methane, which is 20 times more effective than carbon dioxide at trapping heat in the atmosphere. Natural gas is the largest human-caused contributor of methane in the atmosphere.

Taking on the quality of its fossil fuel brethren, natural gas prices are highly volatile, subject to dramatic fluctuations in general economic fundamentals. Following the price levels of natural gas in the past decade, the commodity has hit highs on multiple occasions that are double or triple the relatively low $4 price per million Btu that we currently see under favorable supply conditions.

As is in the nature of a fossil fuel, it has a finite supply. Conventional natural gas is found in pockets and is extracted similarly to how oil is extracted, drilling down and pumping it out. Natural gas also exists as unconventional gas, trapped in layers of shale rock within the Earth's crust. To capture this energy, long pipes are drilled into the ground vertically, followed by a horizontally drilled pipe and from this little fractures are made to release this gas. The gas then escapes up to the surface through pipes. Currently, natural gas global supply estimates are based on a lot of assumptions and thus vary significantly. BP reported 6,608.9 trillion cubic feet (Tcf) of proven reserves, about the same volume as fifteen Lake Superiors (BP 2011). These are known reservoirs recoverable with existing economic and operating conditions. The world is unquestionably consuming its available fossil fuel resources faster than the planet is able to replenish them. Basic economics tells us, as a good existing in finite supply is consumed more and more, its price must rise as it becomes scarcer. Natural gas, if it follows this basic economic principle, could become more costly and less available in the long term.

The IEA estimates current consumption of gas can be maintained for approximately 120 years—250 in the "Golden Age of Gas," if you include unconventional gas sources like shale gas (International Energy Agency 2011). Though this is an enormous amount of energy, today's consumption levels are projected to rise in coming years. Even with efficiency programs and technological improvements in the United States and Europe to curb energy usage, most developing nations will see rapid rises in energy demand as standards of living improve. The IEA expects a 50 percent increase in demand for natural gas over the next 25 years, 80 percent of this consumption coming from non-OECD (Organization for Economic Cooperation and Development) countries. Thus, such estimates, even when factoring in the discovery of new deposits, is a somewhat rosy picture of the availability of natural gas in our future.

With all this being said, it still comes down to costs, and people are driven by costs. For this thesis, the same method of levelizing the cost of energy was applied to natural gas fired electricity generation using combined cycle gas turbine (CCGT) technology. It is important to estimate the LCOE for this technology because it often sets the electricity price in the ISO New England market area (ISO New England Inc. 2006).

Table 4.4 LCOE of Natural Gas by Year

Year	Annualized Cost of Capital ($/kWh)	O&M ($/kWh)	Fuel ($/kWh)	LCOE Total ($/kWh)
2016	**0.0202**	**0.0051**	**0.0302**	**0.0555**
2017			0.0306	0.0559
2018			0.0316	0.0568
2019			0.0322	0.0575
2020			**0.0327**	**0.0580**
2021			0.0321	0.0574
2022			0.0355	0.0608
2023			0.0363	0.0616
2024			0.0368	0.0621
2025			**0.0369**	**0.0622**
2026			0.0379	0.0632
2027			0.0383	0.0635
2028			0.0382	0.0635
2029			0.0381	0.0633
2030			**0.0388**	**0.0640**

Source: Created by author

For Table 4.4, the annualized cost of capital was calculated by starting with the equation $C = (r + d) \cdot q$. Where r and d were the same and q was taken from an IEA report on Estimates of Power Plant Capital and Operating Costs from 2010 and was $1,003 for the Overnight Capital Costs (2010 $/kW). A capacity factor of 85 percent was used which came out to 5,697.9 full load hours (8,766 hrs/yr · 0.85). The O&M costs were also taken from this report and came as both fixed and variable costs. The fixed O&M costs (2010$/kW) were $14.62 and the variable O&M costs were $3.43/MWh. The fixed costs were converted to kWhs by dividing by the full load hours and then added to the variable O&M costs. The fuel costs were calculated by taking the heat rate of 6,430 Btu/kWh, or the amount of fuel energy burned per kWh generated, of an Advanced CCGT, from the same report. This is multiplied by the EIA reference forecast for natural gas prices delivered to New England electric utilities (Energy Information Administration n.d.). Because the EIA price is expressed in $/Mcf, and the heat rate is expressed in Btu/kWh, a Mcf – to – Btu conversion factor of 1,027,000 Btu per Mcf was used. The fuel cost per kWh is therefore equal to 6,430Btu·(price in $/1,027,000Btu). This fuel cost estimate was computed for each year from 2016 until 2030. The fuel cost, O&M cost, and capital costs were all totaled to estimate the LCOE of CCGT generation technology.

V. Social Costs

Social Costs are private costs and the costs of externalities combined. Externalities are consequences, either positive or negative, which occur to a third party not involved in the initial action. Private costs discussed in the previous chapter are simpler to calculate. The problem with externalities is the person causing the problem is not required to pay for it, but rather a third party absorbs the cost. Economists try to level this out so the party responsible is also the party paying. Often externalities are unintended and unexpected, but sometimes they can be predicted. It is difficult in the field of economics to account for this phenomenon seeing as the benefit or cost of an externality is difficult to measure. It rarely comes in monetary form easily implemented in a model. However, external costs, especially in regards to renewable energy are unbelievably important because when included in a comparison between energy types, they can make renewable energies more cost competitive.

When reading a news article about a renewable energy source there are a few arguments that reappear and usually these arguments discuss externalities. The frequently cited negative externalities against wind energy are often related to health costs such as the flicker, noise and vibrations of the turbines as well as the mere sight of the turbines. There are also potential negative environmental and ecological externalities including impacts on bats, migratory birds and local species. For wind, the main arguments for development include the effect it could have on climate change and how energy from wind is one step closer to energy security. There are also arguments for job creation and economic development as well as other environmental benefits if the drilling for oil and gas deceases as a result of substitution of wind energy.

External Costs

Policies and regulations are designed to minimize social costs of projects such as an offshore wind farm. Unlike other new industries lacking regulations, like hydraulic fracturing for natural gas for example, copious amounts of permits and regulations exist for offshore community. Humans have been using the ocean for thousands of years. Mainly regulations have been directed or in response to the oil and gas industry that has caused the creation of such stringent regulations. The controversial and philosophical question of whether governmental regulations are effective in preventing negative externalities from occurring is not the question of this thesis. Instead it will be assumed they are effective and accomplish the goals they are created to solve. This strong link between possible negative externalities of offshore wind energy and policy will be addressed in more detail later.

One of the main arguments against wind power generation in Maine is the negative externalities on health. There are three commonly argued health impacts of wind turbines, although none of them have yet been empirically linked to the turbines. The first of these is flicker. This is when a turbine is geographically located close to a house and the rotation of the blades creates a slow strobe light effect with natural light sources. This problem has not been reported frequently because turbines are generally sited far enough away from houses. The second impact on health is vibrations. Again, this is not generally a problem when turbines are sited far enough away from houses. Noise is also a negative externality. Many people claim it is not only nuisance but also as a cause of lack of concentration and increased headaches among other symptoms. For offshore deepwater wind energy, these negative externalities are assumed to be nonexistent, and therefore have a cost of zero. Similar to properly sited turbines, these costs decrease with an increase in distance from people. The visual impact is also assumed to be zero because with the distance from shore and the curvature of the earth, these turbines will not be visible to people on land. This is where the distinction between shallow-water, fixed-based turbines and deepwater floating turbines needs to be emphasized. Distance solves all of these adverse effects.

There is a fear of collision and/ or the added cost of avoidance if a farm is installed in the Gulf of Maine. This means marine vessels run the risk of running into the turbines. This is a minor concern, and in working with the US Coast Guard to properly site the turbines it should not be a problem.

One of the greatest concerns for the state of Maine in regards to negative externalities is the ecological impact. Most of the data for this comes from European wind farms. Therefore it is only relevant to a degree because not only are the technologies different, but also different ecosystems exist off the coast of European countries in comparison to in the Gulf of Maine. However, that being said, construction of a wind farm in the Gulf could still disrupt habitat, change sediment transportation and water movement, cause changes in migratory patterns, change nutrient regimes, species diversities and community compositions (University of Maine, James W. Sewall Co. 2011).

To address these potential threats, Governor Baldacci established the Maine Ocean Energy Task Force in November of 2008. Since then, studies and information have been compiled and analyzed and more is underway. Jeffery's Ledge, the Eastern Maine shelf and Jordan Basin have all been identified as areas of no development because of the threats to whales, Atlantic salmon, and other species due to the make-up of nutrients in these areas.

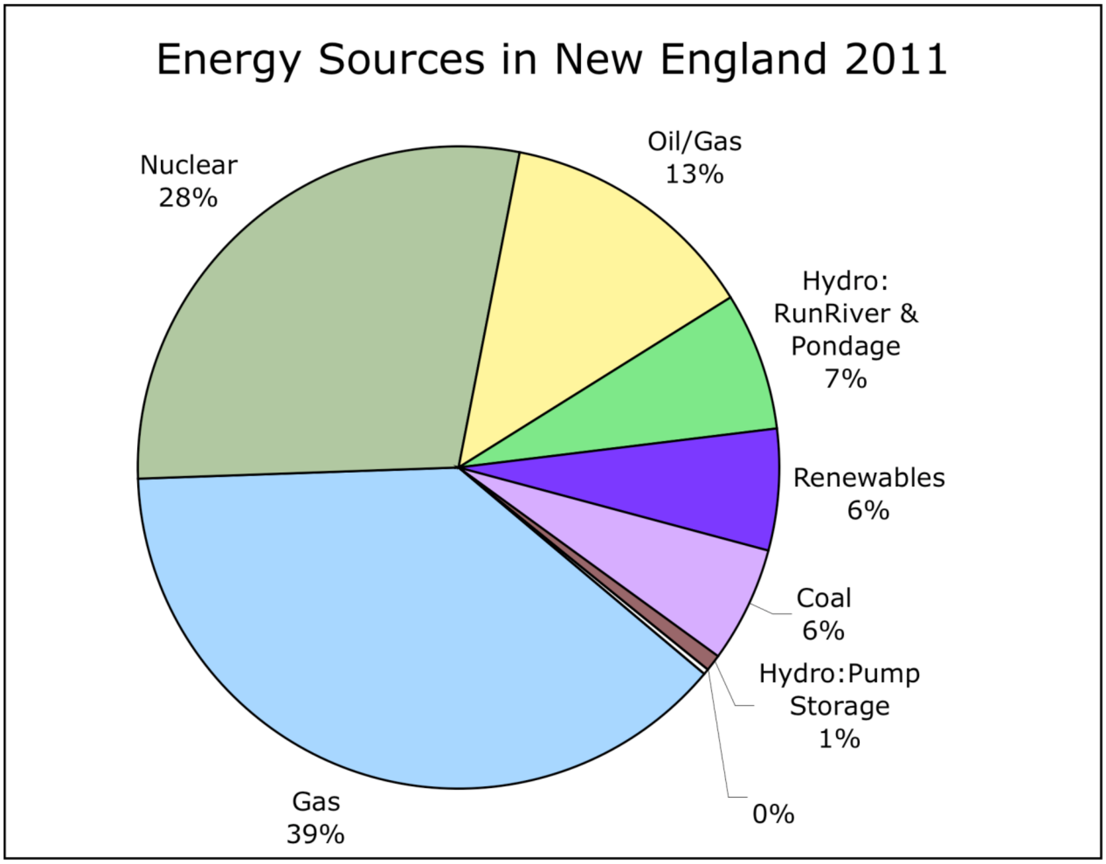
Studies have also been conducted to specifically address the potential effects on birds and bats, especially threatened or endangered species. Habitat loss is an ongoing issue for both bats, who play a crucial role in ecosystems, and migratory birds, who need both wintering and breeding habitats. A migratory bird refers to songbirds, waterfowl, shorebirds, and seabirds. There are about forty species of ducks and geese, about twenty eight species of gulls, one of gannets, six of alcids, about seven of pelagic species, two of cormorants, six of grebes, three of loons, forty of shorebirds, seventeen of wading and marsh birds, and over one hundred and fifty land birds in the Gulf of Maine that breed, migrate or do both in either the coastal or offshore region (University of Maine, James W. Sewall Co. 2011). There is a value to birds in both the ecological sense, especially with bug control, as well as economically, as they contribute to tourism and other various activities. Hence there is a potential externality of wind turbines in the Gulf of Maine. However, extensive studies on all of these effects have been and are currently being done. DeepCwind for example includes the marine biology department whose agenda it is to protect marine wildlife. The hope is before any project would receive approval to begin construction, all potential, foreseeable adverse effects on marine life will have been addressed.

Benefits

Generally speaking, if done correctly, renewable energy is a step in the right direction in regards to climate change and economic development. Offshore wind is like any other business that could be brought to Maine. The current governor refers to Maine as a state “open for business.” This type of development could be one of those businesses. Economic investment within Maine benefits Maine.

In the year 2011 in New England, fifty eight percent of electricity generation came from oil, gas, or coal. Twenty eight percent was from nuclear, eight percent from hydropower, and six percent from renewable sources.

Figure 5.1 Energy Sources in New England 2011



Source: Created by author with data from (ISO New England Inc. 2012)

Oil, coal, and gas are all resources not native to the state of Maine, meaning all of these have to be imported. Most hydroelectricity is imported from Quebec, and natural gas primarily comes from New York or New Brunswick (ISO New England Inc. 2012). It is estimated that about $5 billion leaves Maine each year for energy (DeepCwind Consortium 2012). Maine and New England have a great wind resource at their disposal, and if it can be economically capitalized on, the region can have a more secure source of energy and one that has lower social costs.

Climate Change

A discussion of the existence and proof of climate change is not within the scope of this thesis; the topic as a whole however, cannot be ignored, especially when analyzing a renewable energy source. Climate change has taken the international environmental world by storm as the one of the most pressing problem of the future. “Living green” is not only a fad, but is a popular lifestyle. The biggest challenge when discussing climate change is facing the lack of definite answers. There is a discrepancy among scientist on how quickly action needs to be taken. This is reflected in the carbon pricing models of economists Stern and Nordhaus, with Stern taking a much more aggressive pricing structure. Because of this discrepancy, it is difficult to agree on a proper method to address the issue. There is currently a discussion about whether a two degrees Centigrade temperature increase is the maximum permissible increase prior to taking corrective actions (Commission of the European Communities 2007). So much uncertainty surrounds the issue that it is hard for policy makers to decide what the right steps are.

Although passionately disputed by a few, it is known that the climate is changing. This is one of the motivators behind the development of wind energy. Climate change alone has a whole slew of potential negative externalities pertaining to human health, to agriculture, to water access, and economics as a whole. Wind advocates look to the development of any energy source that avoids adding to this problem as society progresses. The burning of fossil fuels pollutes the air. This pollution has been linked to negative changes in health, like increased asthma rates in the northeast (Schneider 2001). If the development of wind energy is able to decrease the burning of fossil fuels in the

Midwest and therefore pollution, this theoretically and indirectly benefits the health of Americans and maybe people worldwide. The National Academy of Science published a report entitled *The Hidden Costs of Energy* where they estimated the non-climate costs of electricity generation by natural gas were $.16/ kWh in 2007 dollars and $.17/kWh in 2011 dollars (National Academies Press 2012). Granted, these estimates do not have a huge impact on the LCOE, they are still worth mentioning.

Climate change is pretty self explanatory, but with a change in climate comes negative impacts. Some of these might include economic impacts on industries dependent on particular climates. It is easy to see examples of this in the state of Maine. Skiing is dependent on a colder climate, and the entire skiing industry in Maine could eventually collapse if climate change continues on its current path. Blueberry production is also a climate dependent industry. Like all crops, blueberries grow particularly well in a specific climate that just happens to be native to the state of Maine. With increasing temperatures this can easily change. Climate change is not a problem that will be changed or fixed overnight. However, at the rate the world is going unwanted changes will occur, whether they are to health or industry. Regardless if these changes happen now or in fifty years is uncertain, but it is well accepted that changes will occur.

Carbon

To combat this massive issue, economists look at the social costs of carbon and develop carbon pricing policy to incorporate these costs into energy costing and market prices. Many models have been run on the impacts of increased carbon, and therefore climate change, and the purpose of these models is to quantify the negative externality. Basically, a number is calculated for the present value of further economic damages incurred for future tons of CO_2 emissions. Once that number is obtained, policy makers can discuss how to compensate for the externality and make the responsible party pay for the damage instead of the whole world.

As mentioned earlier, calculating the cost of carbon is difficult due to massive uncertainties. To try and account for these uncertainties, multiple scenarios are run. William Nordhaus uses a method called the DICE model, or the Dynamic Integrated Climate and Economy model. The scenarios looked at here will be Nordhaus's carbon price path, another carbon price path that keeps the global temperature below 2˚ centigrade through 2100, and another carbon price path by economist, Nicholas Stern, who uses a much more aggressive pricing regime based off a lower rate of discounting future damages from climate change.

For all scenarios, there is a price ramp due to the increasing damages over time. Nordhaus' scenario tries to balance the damages with consumption growth and avoid inefficiencies in investments. His scenario tries to make substantial long-term impacts with relatively low costs while optimizing consumption over time. The less than two degrees scenario is analyzed because there have been significant reports addressing that a 2 degree centigrade increase in global temperature is when the permafrost will melt, releasing substantial quantities of methane it stores (Commission of the European Communities 2007). Stern's model has an aggressive carbon price path because it uses a low discount rate for future damages to capture his philosophical view of intergenerational justice.

Carbon prices were reported in 2005 dollars per ton of carbon in Nordhaus (2008) and were converted into 2010 dollars per ton of CO_2. The report's time steps of ten years, were linearly inferred in five year increments for this thesis.

Table 5.1 Carbon Pricing: Three Scenarios

Year	**2015**	**2020**	**2025**	**2030**	**2035**
Optimal	46.51	52.89	59.26	66.53	73.80
<2˚C	79.72	96.61	113.50	137.78	162.07
Stern	373.38	453.22	533.07	618.34	703.62
Conversions ($/ton CO_2)					
Optimal	12.68	14.42	16.16	18.15	20.13
<2˚C	21.74	26.35	30.95	37.58	44.20
Stern	101.83	123.61	145.38	168.64	191.90

Source: Calculations by author with data from (Nordhaus 2008)

To be able to compare this information, these numbers were then converted into dollars per kWh. According to a lifecycle assessment report by Weisser in 2007, a combined cycle gas turbine (CCGT) emits 468 grams of CO_2 in its lifetime. This is .0468 kg, or .000468 tons of CO_2 per kWh (Weisser 2007). Therefore, to calculate what the price of carbon is per kWh, this is multiplied by the dollars per ton of CO_2 from the previous table. These calculations are in the following table.

Table 5.2 Carbon Pricing ($/kWh): Three Scenarios and Increased Fracking Emissions

	2015	**2020**	**2025**	**2030**	**2035**
Nordhaus	0.0059	0.0068	0.0076	0.0085	0.0094
<2˚C	0.0102	0.0123	0.0145	0.0176	0.0207
Stern	0.0477	0.0578	0.0680	0.0789	0.0898
50% increased Emissions for fracked NG					
Nordhaus	0.0089	0.0101	0.0113	0.0127	0.0141
<2˚C	0.0153	0.0185	0.0217	0.0264	0.0310
Stern	0.0715	0.0868	0.1021	0.1184	0.1347

Source: Calculations by author with data from (Nordhaus 2008), (Howarth, Santoro and Ingraffea 2012)

In a study done at Cornell University, on the emissions of hydraulic fracturing, or fracking, concluded that emissions from fracked wells are significantly higher because of leaking gas (Howarth, Santoro and Ingraffea 2012). Studies have found emissions to be between forty and sixty percent higher. Here, a fifty percent increase was used to calculate a price per kilowatt-hour for increased emissions from these wells.

For offshore wind energy, the lifecycle assessment is 14 grams of CO_2 (Weisser 2007). This is 0.00014 tons of CO_2 per kWh. The carbon price per kWh is calculated in the same way as CCGT, by multiplying this CO_2 per kWh by the three different calculations each year listed in Table 5.1. These numbers, combined with the CCGT carbon prices are listed in Table 5.3. This table only goes through the year 2030, because that has been the period of analysis thus far.

Table 5.3 Comparison Wind and CCGT Carbon Prices ($/kWh)

	2015	**2020**	**2025**	**2030**
Nordhaus				
Wind	0.0002	0.0002	0.0002	0.0003
CCGT	0.0059	0.0068	0.0076	0.0085
<2˚C				
Wind	0.0003	0.0004	0.0004	0.0005
CCGT	0.0102	0.0123	0.0145	0.0176
Stern				
Wind	0.0014	0.0017	0.0020	0.0024
CCGT	0.0477	0.0578	0.0680	0.0789

Source: Created by author

Table 5.3 presents the final calculations by year for the external costs of each technology. This is the final step before calculating the social costs. To do this, the external costs, in the table above, were added to the levelized private cost of energy values from the previous chapter. This was done for all three carbon estimates for the fifteen-year period of analysis.

Table 5.4 Comparison Wind and CCGT Social Cost ($/kWh)

	2015	**2020**	**2025**	**2030**
Nordhaus				
Wind	0.2473	0.1650	0.1421	0.1335
CCGT	0.0587	0.0621	0.0671	0.0698
<2˚C				
Wind	0.2475	0.1652	0.1423	0.1338
CCGT	0.0630	0.0676	0.0740	0.0789
Stern				
Wind	0.2486	0.1665	0.1439	0.1356
CCGT	0.1005	0.1132	0.1275	0.1402

Source: Created by author

By the year 2030, combined cycle gas turbines and offshore wind energy could be less than a half a cent different in social LCOE. External costs are unbelievably important when it comes to renewable energy because if they are compensated for by carbon prices, it starts putting this cleaner source of energy on a more level playing field allowing it to become economically competitive.

VI: Government Policies

When talking about government involvement in the development of deepwater offshore wind energy, there are two types. The first of these is the permitting and approval involvement. There are numerous agencies that have to approve a project. These range from the US Coast Guard to lead agencies such as NOAA. The second type of government involvement is in financing. This is done through grants, subsidies, and carbon pricing, as discussed in the previous chapter.

In a recent guest lecture on the University of Maine campus, Bill McKibben stated oil and gas companies receive about $20 billion a year in government subsidies. Another report found that from 2002-2008, traditional fossil fuels as a whole received $16.3 billion in direct spending, and $53.9 billion in tax breaks, for a total of $70.2 billion or about $10 billion a year (Thaler 2012). Renewables, in the same repot received $6 billion in direct spending and $6.2 in tax breaks. The point here is that federal subsidies are available. There is money, and it is a matter of how it is allocated.

The next question to be asked is how much would a subsidy be for? This is calculated by an extension of Table 5.4 from the previous chapter to include subsidies. The subsidy required is equal to the difference between the social LCOEs of wind and CCGT and is reported in Table 6.1. The point of this is to allow offshore wind energy to develop, thereby achieving learning driven cost reductions, so that over time market forces can take over and traditional fossil fuels can be phased out as they become uncompetitive on a social cost basis. Therefore, these subsidies are not ambiguous, but rather based on the social cost of other current technologies in the market.

Table 6.1 Estimated Required Offshore Wind Power Subsidies ($/kWh)

	2015	2020	2025	2030
Nordhaus				
Wind	0.2473	0.1650	0.1421	0.1335
CCGT	0.0587	0.0621	0.0671	0.0698
Subsidy	**0.1886**	**0.1029**	**0.0750**	**0.0637**
<2˚C				
Wind	0.2475	0.1652	0.1423	0.1338
CCGT	0.0630	0.0676	0.0740	0.0789
Subsidy	**0.1845**	**0.0975**	**0.0683**	**0.0549**
Stern				
Wind	0.2486	0.1665	0.1439	0.1356
CCGT	0.1005	0.1132	0.1275	0.1402
Subsidy	**0.1481**	**0.0534**	**0.0163**	**-0.0046**

Source: Calculations by author

The calculations done here were simple. The LCOE for CCGT was subtracted from the LCOE for wind energy. What is left is the difference in price per kWh, and therefore the subsidy for wind per kWh. This table includes the effect of learning curves over time, as well as increasing carbon prices over time to capture expected social cost trends. These calculations were also done using the Stern carbon pricing, which is the most aggressive of the three scenarios.

It is projected that in 2030, wind will finally become less expensive on a social cost basis than natural gas. Theoretically at this point, subsidies to wind energy can be cut because wind will be naturally competitive with natural gas. The real question though, is at what point do the savings outweigh the present value of the subsidies. This is difficult to calculate because the savings begin in 2030 under the analysis presented in Table 6.1. To determine on a present value (PV) basis when the energy cost savings of offshore wind are sufficient to offset the subsidy costs requires a projection of cost trends well beyond 2030 which is the end date of this thesis and an assessment of any excess burdens associated with raising revenues to fund the subsidies. These PV and excess burden analyses are outside the scope of this thesis.

Money for this subsidy can come from a variety of sources. One of these, mentioned above, is reallocating the money provided to traditional fossil fuels. There are also a variety of alternative possibilities. One of these is a tax credit. Up to expire, and potentially be renewed, this year is the Production Tax Credit (PTC). This has been one of the main sources of fuel behind renewable energy investment in recent years. The PTC is an income tax credit of 2.2 cents per kWh. It was an incentive created under the Energy Policy Act of 1992. The American Recovery and Reinvestment Act of 2009 also provides options for wind developers. In place of the PTC, a developer can chose a 30 percent investment tax credit (ITC), or a 30 percent Energy Department grant which does not require any tax appetite to have its maximum impact on lowering CAPEX to the developer. As mentioned, the PTC is due to expire at the end of 2012. Waiting to renew the policy has created a slow in the development of wind power because some developers are reliant on this break to compensate for the high investment. With a goal of 20 percent of electricity coming from wind power by the end of 2030, as set under the Bush administration, it could be detrimental to not extend this tax credit.

Another option is a feed-in tariff. This is a policy where wind power generators would be offered long-term, usually government-backed, contracts based on the cost of the electricity generation where the buying of the electricity and carbon credits is guaranteed. The benefit of a feed-in tariff is that they are extremely secure. This system is widely used in Germany with significant success (Cory, Couture and Kreycik 2009). Generally feed-in tariffs decrease over time, this is referred to as a degression of tariffs. The reasoning for this feature is that the required subsidy is expected to fall over time as learning effects occur and carbon prices rise (as occurs in Table 6.1).

Fulfillments of Renewable Portfolio Standards by individual states as well as bonus depreciation by the IRS are other options for policies that could benefit the offshore wind energy industry and their demand for subsidies to make them economically viable. Wind could also be considered a tax-exempt entity. The IRS has administered Clean Renewable Energy Bonds trying to incentivize the financing of wind projects. Grants are also a simple straightforward way of financing wind projects. The Department of Energy provides loan guarantees and grants companies can apply for. These are all just a few options. There are copious amounts of possible policies available for offshore wind energy if made available by federal legislations.

VII. Conclusion

Climate change is and will continue to be an issue. The best the world can do is to force policy makers to pass laws about climate change regulation. What has been covered in this thesis are calculations based on assumptions. These assumptions are based on research and logic, but when it comes down to knowing exactly what is going to happen in the future, it is impossible to predict. The best solution is to run models and find a way to remedy the problem before it happens.

Learning curve effects and carbon pricing are key factors in making this world livable in the future. These are the steps to make renewable energy, in this case offshore wind, viable and competitive in the market. Policy makers need to ensure investment now continues to happen in the offshore wind industry because if not, learning curve effects will never take place. Carbon pricing works in conjunction with the learning curves and speeds up the process of scaling up the offshore wind industry as well as making progress on mitigating climate change.

The analyses conducted in this thesis are not perfect. The initial capital costs were conservatively estimated. A proper capacity factor has not yet been determined for Gulf of Maine offshore turbines, but the estimates relied on all appear to be reasonable from the vantage point of our current understanding of the Gulf of Maine wind resource. However, these are the assumptions that need to be made, and perhaps various errors may cancel out. At the very least, these numbers provide empirical analyses on which policies and decisions can be based. This might not be dead-on when these technologies finally go through, but it is important for people to understand the trends that will be seen and the differences a few governmental steps could make.

Natural gas is a dangerous commodity to rely on for the future. Historically gas prices follow the fluctuations of oil prices. Also, with the new, pressing issue on fracking, the supply of natural gas, especially domestically is unreliable. If in the next couple of years fracking is as dangerous as some instances have already shown, who’s to say it will not be regulated to the point where there are serious price increases?

Another idea, which has gained more and more popularity in recent years, is the idea of natural gas being a bridge. Clearly with the current infrastructure and stage of technology immediately switching entirely off of fossil fuels is not an option. However, natural gas does have some benefits that need to be recalled, mainly that it is cleaner than coal. Perhaps, in the coming years the base load will be natural gas with wind on top and gradually will switch to wind as the base load with natural gas substituting in when there is an increase in demand. One of the reasons this could be effective is because natural gas plants are easily turned on and off.

When it comes down to it, if the right steps are taken, offshore wind electricity generation could become competitive with natural gas. However, as it currently stands deepwater offshore wind electricity generation in the Gulf of Maine is not viable. Learning curves, carbon pricing, and possible federal subsidies need to happen for this resource to be able to compete. Wind is renewable and clean. If the proper policies are developed, this clean, renewable future could be ours.

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Upon graduation, Caitlin is working at an all girls' summer camp teaching waterskiing while looking for a more permanent position. She hopes to travel to South America and further her Spanish speaking skills as well as eventually attend law school to become a permitting lawyer for renewable energy projects.