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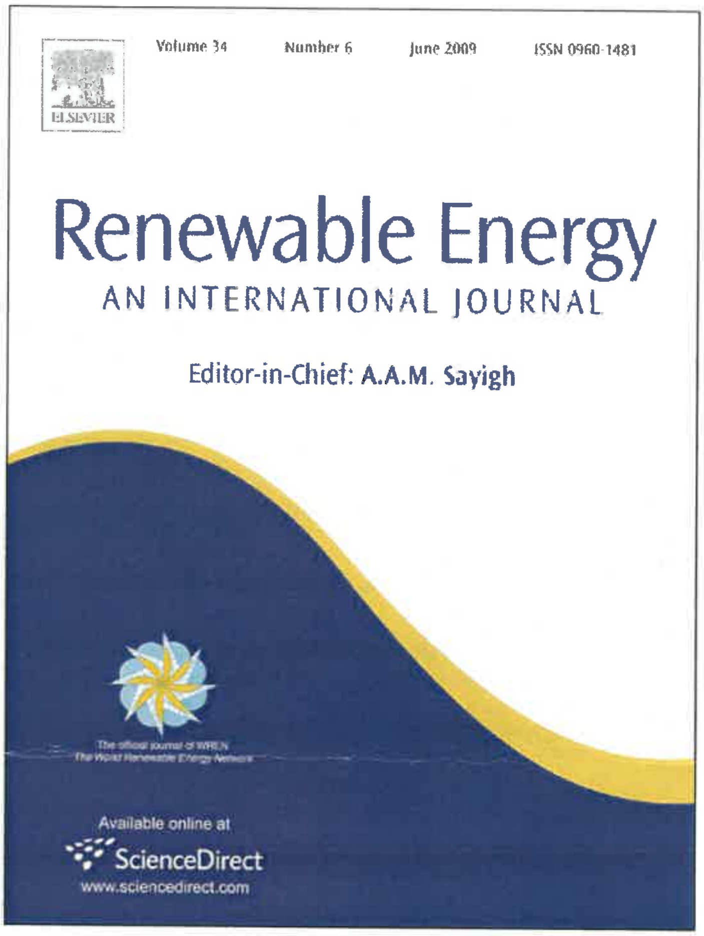

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Ecological and economic cost-benefit analysis of offshore wind energy

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ABSTRACT

Wind energy has experienced dramatic growth over the past decade. A small fraction of this growth has occurred offshore, but as the best wind resources become developed onshore, there is increasing interest in the development of offshore winds. Like any form of power production, offshore wind energy has both positive and negative impacts. The potential negative impacts have stimulated a great deal of opposition to the first offshore wind power proposals in the U.S. and have delayed the development of the first offshore wind farm in the U.S. Here we discuss the costs and benefits of offshore wind relative to onshore wind power and conventional electricity production. We review cost estimates for offshore wind power and compare these to estimates for onshore wind and conventional power. We develop empirical cost functions for offshore wind based on publicly reported projects from 2000 to 2008, and describe the limitations of the analysis. We use this analysis to inform a discussion of the tradeoffs between conventional, onshore and offshore wind energy usage.

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1. Introduction

Over the past 10 years, the onshore wind industry in the U.S. has grown dramatically and as a result developers, citizens and the U.S. Congress have expressed interest in the development of an offshore wind industry. Several companies have developed plans for offshore wind projects and the U.S. Mineral Management Service (MMS) is in the process of reviewing these applications and developing regulations for the industry while the state of Texas has already leased lands for at least one and possibly several additional offshore wind farms. Lawmakers, government agencies, corporations, non-governmental organizations and private individuals are deciding whether or not to support or participate in the development of an offshore wind industry, and the relative level of support or encouragement to give this new industry. In making these decisions, stakeholders will have to balance the ecological costs and benefits of offshore wind against its economic costs and compare to offshore wind energy's most realistic competitors. The decision is complex and requires balancing local and global environmental issues, historical conservation and economic costs.

Offshore wind energy competes with both onshore wind energy and conventional fossil-fueled electricity. Onshore wind power and natural gas fired power are the two fastest growing segments of the electricity market. Coal power is the largest current producer of electricity in the U.S. Offshore wind will thus displace either coal, natural gas or onshore wind.

Given the uncertainties associated with global climate change, it is difficult to compare the societal costs and benefits of wind energy to fossil-fueled energy. However, one way to develop a first-order comparison of these costs would be include the costs of market based carbon offsets in the costs of conventional electricity. This assumes that the costs of carbon emission credits accurately reflect their ecological value which would occur if carbon credits actually represent a reduction of the specified amount of carbon dioxide from the atmosphere.

It is perhaps less difficult to compare the costs of onshore and offshore wind energy since they both have similar carbon emissions. In this case, one could simply compare the economic and ecological costs of onshore and offshore wind.

There are several reasons why developers or lawmakers might prefer offshore wind power over fossil-fueled power or onshore wind power. Offshore wind power could be less expensive than its competitors, either at a local or national scale, it could have the potential to be less expensive than its competitors, or it could have less severe social and environmental impacts than its competitors.

In this paper, we seek to address the question, "Is investment in offshore wind power preferred over investments in fossil-fueled or onshore wind power?" We focus primarily on coal-fired power as representative of fossil-fueled power since it is the dominant source of electricity in the U.S. and it is both inexpensive and a major source of greenhouse gases.

We begin with an overview of the commonly expressed criticisms and benefits of offshore wind power. We discuss cost models for offshore wind power and compare them to onshore wind power and conventional power. We also discuss the factors that lead to higher costs through a first-order empirical cost function and

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discuss how these costs can be decreased. We discuss the environmental impacts of offshore wind power and how these factors can be mitigated. We end the paper with the conclusions of the analysis.

2. Criticisms of offshore wind power

There have been a number of criticisms on offshore wind power in the U.S., mostly associated with the Cape Wind project (Table 1, [1,2]). The environmental impacts are discussed in more detail below, the rest of the concerns are discussed here.

2.1. Navigational safety

Any structure placed in federal water must receive a permit from the Army Corps of Engineers (ACE). The ACE, through the Rivers and Harbors Act (RHA), has the authority to regulate obstructions to navigation in federal waters. The ACE considers a multitude of factors in making RHA decisions, however, their primary responsibility is protecting navigation, therefore they are unlikely to permit offshore wind projects that pose serious threat to U.S. shipping lanes. However, densely spaced wind turbines could provide a problem for recreational boats and small fishing vessels attempting to navigate through a wind farm. Typically, turbines in a wind farm are spaced 500–1000 m apart and have blades that at their lowest point are at least 20 m above the water. Small boats should therefore have no problem navigating among these turbine in good weather, however, some critics of the Cape Wind project have pointed out that the coast of Massachusetts is infamous for bad weather and shipwrecks. This is likely to be the case in many places in which offshore turbines are particularly profitable (i.e. areas with high winds).

2.2. Federal subsidies

Opponents of offshore wind projects claim that offshore wind power is not economically viable without federal "subsidies", by which they mean federal tax credits for renewable energy. The federal Production Tax Credit (PTC) gives a tax credit of $0.02/kW h of produced electricity for the first ten years of production from any renewable source, including wind.[1] Opponents of the PTC argue that its original purpose was to help the renewable energy industry become established and because it originally became law in 1992, it should now be allowed to expire. In fact, the PTC did expire in 2000, 2002 and 2004 and is currently set to expire at the end of 2008. Interestingly, the pattern of wind capacity growth in the U.S. seems to closely follow the expiration of the PTC [3]. In each of the years in which the PTC was allowed to expire, the growth in wind capacity slowed markedly. Given the relatively unfavorable economics of offshore wind, it is reasonable to suggest that offshore wind energy projects will need the continuation of the Production Tax Credit (PTC) in order to be competitive.

2.3. Aesthetics

Opponents to wind power claim that wind turbines mar the landscape or seascape. This is especially an issue for the Cape Wind project in which local activists are concerned about the views from historic landmarks. There are some aesthetic issues that are beyond the scope of analytic tools, however, the effects of wind farms on property values has been analyzed. Sterzinger et al. [4] analyzed property values in the viewshed of onshore wind turbines and found that in eight out of ten cases the property values in the viewshed increased faster than the values in control sites. Furthermore, in nine of ten cases the rate of property value increase rose after the placement of the wind farm. Thus, there is no empirical evidence to suggest that wind farms negatively influence property values.

In Denmark, Ladeenburg and Dubgaard [5] estimated the willingness of citizens to pay for moving turbines further from shore. They found that respondents were willing to pay 46, 96 and 122 Euros per year per household in order to move a theoretical wind farm to 12, 18 or 50 km away from the coast, relative to an 8 km baseline [5]. Huaghton et al. [6] conducted a similar study on Cape Cod and found that 22% of respondents were willing to pay, on average, a onetime cost of $286 for windmills to not be built, while 9% were willing to pay an average of $112 for windmills to be built. The average net willingness to pay per person was $75. These data suggest that on average the public views offshore wind turbines as visual disamentities, at least before they are built.

2.4. Cost and risk

The offshore environment is significantly more uncertain and difficult than onshore, and thus, more costly and risky. The offshore environment involves personnel traveling to and from offshore turbines; this increases equipment and time costs as well as insurance costs due to increased risks. Offshore work involves increased risks of storms which affect the amount of time available for maintenance and installation which in turn influence capital and operation costs. Offshore environments are corrosive to electrical and structural equipment and require turbines to be marinized with cathodic and humidity protection. Capital expenditures for offshore wind projects depend on marine vessel dayrates which are unpredictable, and offshore foundations require more steel for jackets and pilings than onshore foundations.

2.5. Unpredictable power

One of the most substantive criticisms of wind power is that it is unable to provide constant, predictable power to the grid. The electricity grid is designed to send a constant AC load to consumers and it relies on large power plants producing predictable and steady electricity. Wind energy is not steady and varies on the scale of minutes, hours, days and months and the changes in wind power output are difficult to predict ahead of time [7]. Therefore, integrating wind power into the electricity grid will require backup systems (especially natural gas fired power plants) that can respond quickly to changing production from wind farms [8]. This increases the total national cost of electricity. The DOE has estimated that the supply up to 20% of the nation's electrical use from wind power would cost up to $5/MW h in integration costs [9].

3. Benefits of offshore wind power

Offshore wind power shares all of the same benefits of onshore wind power relative to conventional power sources (Table 1). Most notably, wind power has very low carbon emissions over its lifecycle, as well as negligible emissions of mercury, nitrous oxides and sulfur oxides. Wind power does not use fuel and is therefore freed from the price volatility associated with electricity generated from oil, natural gas, biomass, nuclear and coal. Wind power does not rely on large sources of freshwater as conventional sources of power do [9]. In the near term, offshore wind power will be more expensive than onshore wind power, however, there are several benefits of offshore wind power that are not shared by onshore wind; these benefits may or may not justify the additional costs.

[1] For example, if a 400 MW wind farm has a capacity factor of 50%, then it would produce about 1.7 billion kW h of electricity annually, and would qualify for 35 million dollars in tax credits each year for the first ten years of its operational life.

Table 1
Summary of arguments for and against offshore wind and comparison to onshore wind.

	Applies to onshore wind power	Validity
Arguments against offshore wind		
Ruins special/historic seascape	Y	Aesthetics subjective, but wind turbines are visual disamenity to most. No effect on property values.
Kills birds	Y	Expected death rate 1–10 birds per MW. Difficult to compare effects of wind and fossil fuels on bird populations on a per MW h basis.
Harms fisheries	N	Likely to be significant impacts on local fisheries during construction, especially if monopiles are used. During operation fishing success may increase.
Harms marine mammals	N	Likely to have impacts on marine mammals during construction, especially if monopiles are used, potentially including mortality. During operation impacts will be negligible.
Requires subsidies	Y	Offshore wind power not economically competitive with onshore wind or fossil-fueled power.
Endangers shipping/navigation	N	Site dependent. USACE must permit projects and decide if they threaten navigation.
Hurts tourism	N	Offshore wind projects have caused net increases in tourism.
Arguments for offshore wind power		
Mitigates climate change	Y	Wind power produces very little greenhouse gas emissions over its life cycle.
Decreases water use	Y	Each MW of wind capacity can offset 0.7–2.1 million gallons of water consumed per year
Improves air quality	Y	Cape wind estimated to prevent 11 mortalities per year (Kempton et al., 2005), but depends on fuel mix of power actually displaced.
Reduces foreign fuel dependence	Y	Roughly 50% of U.S. electricity comes from coal; U.S. exports more coal than it imports. Roughly 20% of electricity from natural gas. Roughly 20% of this natural gas is imported, almost entirely from Canada.
Creates jobs	Y	The Cape Wind project will create about 50 permanent jobs, plus 100 indirect jobs. Construction will create several hundred additional jobs.
Creates electrical price stability	Y	Wind power provides price stability since cost of producing energy can be forecast, but even most ambitious plans only imagine 20% of U.S. electricity supply to come from wind in 2030.
Close to population centers	N	Offshore sources are closer to population centers than onshore wind sources, but it is probably cheaper to build new transmission systems from high-wind onshore sites.
Higher winds offshore	N	Winds are more powerful offshore, but COE of offshore wind is higher than COE of onshore wind, suggesting that higher wind speeds do not make up for higher capital costs.
Reduced user conflicts	N	Site and plan specific; seems to be occurring in Texas, not in Cape Cod.

3.1. Location

Onshore wind resources in the U.S. are localized in the middle of the country, far away from large population centers. Offshore wind power is physically close to the major population centers of the coastal United States, thereby removing the need for expensive high voltage transmission [10]. However, with a large enough investment, it may be more efficient to build these transmission lines then it would be to invest in offshore wind power. Recent studies have evaluated the costs of producing 20% of the nation's electricity from wind (primarily onshore wind). The cost to transmit this electricity from the wind centers of the west and midwest to the population centers on the coasts has been estimated to be about $20 to $26 billion. This would add about $120 to $180 to the capital costs of new construction making total capital costs about $2000/kW, below current offshore costs of around $3000–4000/kW [9].

Onshore wind power, in some cases, has been stalled by local opposition due to conflicts between alternative land uses [11]. One potential benefit of offshore wind is that it may reduce this conflict [12]. Wind turbines can be placed far enough from the shore to be inaudible and, potentially, invisible. Local opposition to the Cape Wind project remains strong, but does not seem to be the case in the Galveston Offshore Wind Project [13].

3.2. Power

Offshore winds are generally stronger and more constant than onshore winds. As a result, turbines are expected to operate at their maximum capacity for a larger percentage of the time, and the constancy of wind speed reduces wear on the turbine and provides a more constant source of power to the electrical grid reducing the need for other sources of electricity to serve as backups [14]. The increase in wind speed leads to a 150% increase in electricity production for offshore wind turbines [15] and an increase in the capacity factor of the wind farm from about 25 to 40% [16].

3.3. Transport and construction

The marine cranes developed for the offshore oil and natural gas industry are capable of handling larger equipment than onshore cranes, thus allowing for larger turbines to be efficiently erected at sea. The transportation of the required enormous pieces of equipment is also made significantly easier at sea [17]. The size of onshore turbines is limited by the ability to transport the blades, tower and nacelles of the turbines. As a result, cost reductions due to the economics of scale are limited. However, at sea these constraints are not an issue and wind turbines already exceed 5 MW and may eventually exceed 10 MW. These larger turbines may make offshore wind power more economically attractive due to the economies of scale.

3.4. Design considerations

Offshore wind power also has several potential benefits that have not yet been realized due to its nascent nature; these benefits are related to the potential for new turbine designs optimized for the offshore environment [18].

Turbine noise is an oft-cited criticism made by opponents to onshore wind power [19]. The offshore wind power industry does not have to be as concerned about turbine noise as does the onshore industry. As a result, the offshore industry can use far larger turbines [17]. These larger turbines should make offshore wind power more economically attractive due to scale economies. Additionally, if offshore turbines are freed from constraints of noise, then turbine manufacturers could build turbines with downwind rotors, that is, rotors that are located behind (with respect to the wind direction) the support tower and nacelle. In upwind rotors, extreme wind speeds could deflect the blades back toward the tower. Thus the blades have to be made very stiff, increasing their price and weight (the increased weight also increases the expense of the tower, foundation and construction). In a downwind rotor the blade can be more flexible. However, as the blades pass through the wind shadow caused by the tower they create a low frequency noise. Offshore wind farms would not need to be as concerned with this noise [20].

Offshore wind farms located over the horizon could also make use of lattice towers instead of tubular towers. These lattice towers require less material and are therefore lighter and cheaper than the more common tubular towers, however, they are rare for aesthetic reasons [21]. Similarly, two bladed turbines were rejected by the European market for aesthetic reasons [20], however they are lighter (and therefore less expensive) than three bladed turbines.

4. Cost estimates of wind power

The economic costs of conventional, onshore and offshore wind power are shown in Table 2. The estimate for conventional power comes from an average of all power generation in the U.S. There is a great deal of variation in the estimates for offshore wind costs which is due to the assumptions of the analysts and the year in which the estimates were performed. Commodity prices have increased significantly in recent years, and the costs of turbine construction and installation have also increased, both onshore and offshore. Additionally, the methodology through which cost estimates are made, and their potential application can differ significantly. What is clear is that the costs of onshore wind power are competitive with conventional power sources, but that the costs of offshore wind power are more expensive than either onshore or conventional electricity perhaps by a factor of 2–3. The exact price of the premium is time and site specific, but may be up to $50/MW h. Since onshore wind is cost competitive with conventional electricity, the premium is similar for both energy sources and may be higher for onshore wind than for conventional power.

4.1. Costs of onshore wind power

Data on the costs of offshore wind power is relatively sparse due the limited number of installations and the lack of reporting. Data on onshore wind power costs are more readily available. The price of onshore wind generated electricity (cost of energy; COE) declined from 1999 to 2005 from approximately $63/MW h in 1999 to $36/MW h in 2005. However, in 2006 the price began to rise again and in 2007 the price of wind generated electricity was $40/MW h (all prices in 2007 dollars). Even with this increasing price, wind power is competitive with conventional power sources; since 2003 wind generated electricity has been at or below the average national wholesale price of power.

Part of this rising price is attributed to the rising capital costs of wind farms. From the early 1980s to the early 2000s, capital costs of wind farms declined by $2700/kW. From 2001 to 2003 the capital costs for onshore wind farms averaged about $1450/kW; by 2007 these costs had risen to $1710/kW. These increasing project costs are due to increasing turbine costs which have increased as demand and commodity prices have grown.

The primary drivers of the COE are the capital costs of a wind farm and the capacity factor. COE increases with the capital costs and decreases with the capacity factor [22].

Table 2
Capital costs and cost of energy of offshore wind farms.

Wind farm or type of estimate	Year of prediction/ estimate	Cost of energy ($/MW h)	Capital costs ($/kW)	Source
Generating costs of coal-fired electricity	2003	49		[60]
National average wholesale price of power (primarily coal, gas and nuclear)	2008	58		[22]
Generic estimate based on empirical data (Onshore)	2008	40	1710	[22]
Generic estimate based on small set of empirical data	2005	40–95	1600–2600	[64]
Theoretical w/3 MW turbine	2006	95	2100	[23]
Theoretical 500 MW farm, 5 MW turbines, 15 miles from coast	2004	54	1200	[17]
LIOWP (cancelled)	2007	291	5231	[25]
Generic estimate for future wind farm	2007		4000	[25]
General based on empirical data	2007	100	3200	[33]
Cape Wind	2007	122		[65]
Estimates from proposed wind farms	2001	48–70		[66]
Generic estimate based on all available empirical data	2008		3354	Data in Table 3
Middelgrunden	2005	70		[26]
Theoretical Generic estimate	2006		3500	[18]
Empirical data	2003		2200–2600	[62]

4.2. Offshore cost estimates

Musial and Butterfield [17] developed a model of the costs of offshore wind farms. They modeled a hypothetical 500 MW wind farm composed of 100, 5 MW turbines. The farm was in shallow water, 15 miles from the coast. They assumed that the turbines would cost $340 million, the foundations $100 million and the electrical connections $160 million. This gave a total construction cost of $1200/kW and a cost of energy of $54/MW h.

Fingersh et al. [23] modeled the costs of a single 3 MW turbine in shallow water, but included the per turbine costs of electrical interconnection. The cost of electricity was a function of the annual expenses divided by the annual energy production. The annual expenses included the rate of return on the initial capital investment (11.85%) times the initial capital required ($6.3 million; $2100/kW) plus the land lease costs ($12,000), operation and maintenance costs ($215,000 per year), and replacement and overhaul costs ($55,000 per year). Fingersh et al. assumed a capacity of 38% and predicted the total costs to be $95/MW h. They used a similar method to estimate the costs of onshore wind power and found them to be roughly half the costs of offshore wind power.

In the now defunct Long Island Offshore Wind Park (LIOWP) agreement between FPL Energy and the Long Island Power Authority (LIPA), LIPA agreed to pay $94.97/MW h for offshore produced wind power. This rate was designed to increase annually at 2.75% [24]. PACE Global Energy Services conducted an independent report for LIPA and found that the costs of construction were approximately $750 million ($5231/kW). This translated into a cost of energy of $291/MW h. PACE also estimated the costs of a future (2010) generic European offshore wind farm at $4000/kW. This high cost is due to the increasing price of materials [25].

4.3. Cost components

The primary component costs for on and offshore wind based on empirical studies are shown in Fig. 1. The primary capital cost for onshore wind projects is the turbine; installation costs make up about 14% of the total capital costs. For offshore wind projects, the costs of installation is higher, approximately 20% of the total costs and the costs of building and installing the foundations account for another 20% of capital costs. For offshore wind, operation and maintenance costs make up a larger proportion of the overall components of the COE [23]. This is likely due to the costs of accessing offshore wind farms and maintaining turbines in operating condition.

5. Offshore cost functions

5.1. Data source

We have compiled data from a variety of public sources on the costs of offshore wind farms built in Europe (Table 3). Construction

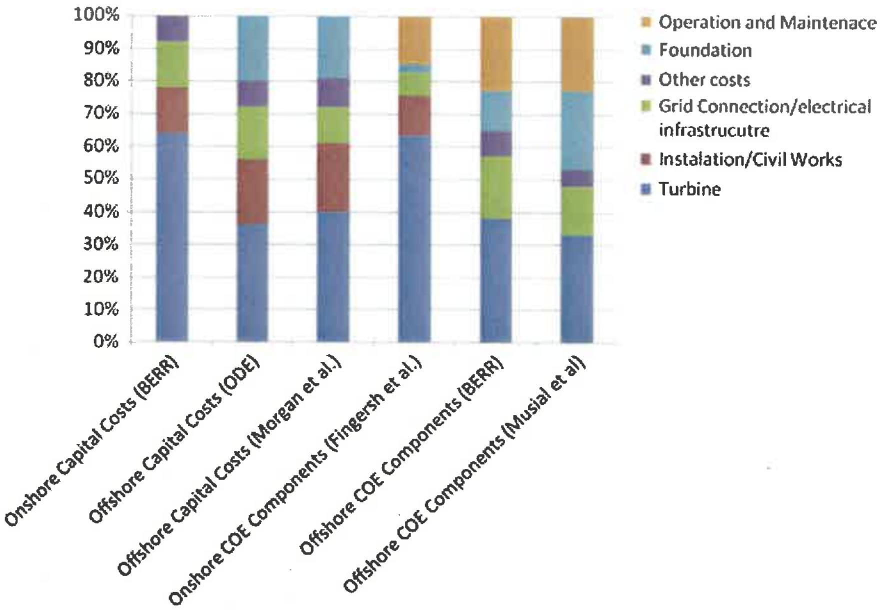

Fig. 1. Costs of onshore and offshore wind. Sources: [23,31,33,62,63].

costs have ranged in price from $1462 to $7000/kW of capacity and average $3354/kW of capacity. Excluding Beatrice, estimated costs for not yet completed wind farms and developments built before 2000, construction costs for wind farms built between 2001 and 2007 ranged from $1462 to $3125/kW. We believe the smaller sample is more representative of general trends and use it for all further analyses.

These data come from a variety of sources including developer websites which we cannot independently verify. These data may not reflect the entire costs of construction in all cases such as the cost of transmission studies and permitting. The cost data were inflated to 2008 dollars by converting the original cost to dollars using the average exchange rate in the year in which the estimate was given (assumed to be the year of construction unless otherwise indicated), then inflating to 2008 dollars using the U.S. Bureau of Labor Statistics calculator.

5.2. Model specification

We created multiple regression models of capital cost based on several factors. We hypothesized a cost model in which the predictor variables were total capacity, water depth, distance to

Table 3
Costs of offshore wind farms in Europe.

Wind farm	Nation	Year constructed	Capacity (MW)	Total cost[a] (million)	Depth (m)	Turbine size (MW)	Number of turbines	Distance to shore (km)
Vindeby	Denmark	1991	5	11.2	3.5	0.45	11	1.5
Lely	Netherlands	1994	2	4.8	7.5	0.5	4	0.8
Tuno Knob	Denmark	1995	5	11.2	4	0.5	10	3
Dronten	Netherlands	1996	11	28.6	1.5	0.6	19	0.03
Bockstigen	Sweden	1997	3	4.8	6	0.55	5	
Blyth	UK	2000	4	7	8.5	2	2	1
Middlegrunden	Denmark	2001	40	53	6	2	20	2
Utgrunden	Sweden	2001	10	14	8.6	1.425	7	
Yttre Stengrund	Sweden	2001	10	18	8	2	5	
Horns Rev	Denmark	2002	160	500	10	2	80	14
Nysted	Denmark	2003	158	373	7.75	2.3	72	10
Samso	Denmark	2003	23	52	20	2.3	10	3.5
North Hoyle	UK	2003	60	148	12	2	30	7
Ronland	Denmark	2003	17.2	26	1	2.3	8	
Scroby Sands	UK	2004	60	155	16.5	2	30	2.5
Arklow	Ireland	2004	25	70	3.5	3.6	7	10
Kentish Flats	UK	2005	90	217	5	3	30	10
Barrow	UK	2006	90	190	17.5	3	30	7.5
Egmond aan Zee	Netherlands	2006	108	334	18	3	36	10
Burbo Bank	UK	2007	90	185	5	3.6	25	6.5
Beatrice	UK	2007	10	70	45	5	2	22
Lillgrund	Sweden	2007	110	300	7	2.3	48	10
Q7	Netherlands	2007	120	590	21.5	2	60	23
Lynn/Inner Downsing	UK	2008	90	600	9.5	3.6	54	5
Robin Rigg	UK	2008	180	765	5	3	60	9
Throton bank	Belgium	2008	300	1250	14	5	60	27

Sources: [18,26,64,66–75].
[a] Adjusted for inflation using the Bureau of Labor Statistics calculator and exchange rates at the time of construction.

shore, year constructed, turbine size, and number of turbines. We had no reason to assume that any interaction or higher-order terms would be appropriate.

5.2.1. Total capacity

Obviously, increasing the size of development will increase the capital costs of the project and this parameter is needed in the model in order to control for varying sizes of developments. However, the costs are unlikely to scale linearly with the size of development. Installation costs, and grid connection costs, and even turbine costs are unlikely to scale linearly with the size of the wind farm. For example, for orders of over 100 turbines there is approximately a 30% reduction in the list price [16]. Nonetheless, we expect that the total capital costs will increase with increases in total capacity.

5.2.2. Turbine capacity

There is a clear trend toward increasing turbine size in onshore [22] and offshore applications. This could decrease costs since larger capacity turbines would require fewer foundations for the same sized wind farm, however, larger components require larger barges and cranes for construction which are less common and more expensive than smaller barges. There is no relationship between turbine capacity and the per kW capital costs of offshore wind farms (Fig. 2) and so we do not hypothesize relationship between increasing turbine capacity and capital costs.

5.2.3. Distance to shore

The distance to shore influences both the construction and operation and maintenance costs. During construction the ships will have to make a number of trips between the site and shore to load additional equipment. This travel period is costly and therefore the closer an offshore site is to an industrial port facility, the less expensive installation will be. Furthermore, the distance to shore also dictates the amount of transmission cabling required. During operation a maintenance crew will need to make regular trips to the wind farm to monitor the foundations, towers and turbines [26]. Locating this crew as close as possible to the wind farm will decrease both the environmental impacts and the costs of maintenance. We expect distance to shore to be positively related to capital costs.

5.2.4. Water depth

Water depth is a primary factor in most offshore operations in the oil and gas industry, and thus we suspect water depth will also eventually play an important role in determining costs as offshore wind farms are installed in ever deeper water. Increasing depths increase the price of construction by making monopile and gravity foundations impractical and potentially requiring the use of expensive, jacketed foundations and expensive marine vessels for installation. Shallow water can restrict the access of some large barges which could also restrict operations. Many cable laying vessels have deep drafts (up to 8 m); therefore shallow water may necessitate the use of remotely operated vehicles (ROVs) for cable laying operations. Use of ROVs and divers in offshore construction will significantly impact costs.

5.2.5. Year of construction

There is a general expectation that technological learning will cause the cost of offshore wind installations to decrease [16]. This has occurred in the onshore wind industry with consequent expansion in capacity, and there is a great deal of expectation that a similar phenomenon will occur in the offshore wind industry. Year of construction may be negatively associated with capital costs, but we do not suspect that the sample set is sufficiently large to detect such effects.

5.3. Model results

We checked the variables for colinearity using a correlation matrix and found no parameters with correlation coefficients greater than 0.7. Therefore, we left all parameters in the model and applied various combinations of the 5 parameters and ranked the models according to their adjusted R^2 value. The models and their parameter estimates are given in Table 4.

Three variables common to all three of the best models were total capacity, distance to shore, and turbine size. As expected, costs increased with increases in total capacity and distance to shore, and decreased with increases in turbine size. The year of construction and water depth were not significant in any of the models. The water depth value from the sample set ranged from 1 to 21 m which is not sufficient to detect depth effects. The cost element is also too gross to expect time to play a significant role in the model.

5.4. Limitations of analysis

The capital costs of offshore wind farms is governed by conditions unique to the structure, site contractor and country as well as the prevailing environmental, engineering, market, operational, and regulatory conditions at the time of the operation. The unique nature of the offshore operations and construction objectives drives the variability observed and can only be partially explained through factor analysis.

6. Managing costs

With a COE of up to $100/MW h (Table 2), offshore wind is not currently cost competitive with either onshore wind or conventional electricity. However there are a number of factors which may

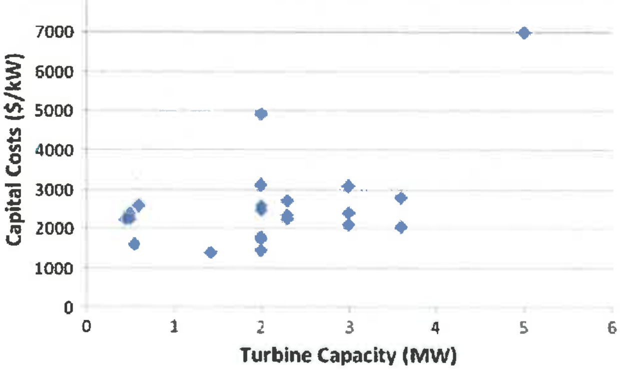

Fig. 2. Capital costs versus turbine size.

Table 4
Parameter estimates from the three best models from multiple regressions.

Total cost (million $) = $\beta_0 + \beta_1^*$ (year) + β_2^* (distance to shore (m)) + β_3^* (turbine size(MW)) + β_4^*(capacity (MW)) + β_5^*(water depth (m))

Parameter	Model 1	Model 2	Model 3
β_0	−21,029 (0.2281)[a]	18.02 (0.6929)	−19,293 (0.2890)
β_1	10.53 (0.2271)		9.66 (0.2887)
β_2	9.28 (0.015)	9.97 (0.0007)	8.43 (0.0111)
β_3	−56.14 (.0204)	−39.06 (0.0346)	−57.68 (0.0229)
β_4	2.45 (<0.0001)	2.65 (<0.0001)	2.53 (<0.0001)
β_5			1.05 (0.5825)
Adj R^2	0.92 (<0.0001)	0.91 (<0.0001)	0.91 (<0.0001)

[a] P-values reported in parenthesis.

lead to significant cost reductions in the future and there are many factors that may make offshore wind locally attractive.

The COE for offshore wind power is determined by the capital costs of installation, the interest rate, the operation and maintenance costs, and the energy produced. Offshore wind developers have little control over some of these factors (e.g., the interest rate), but site selection and project planning can reduce costs and increase revenues. Furthermore, the costs of offshore wind may decrease over time due to technological learning.

6.1. Factors influencing revenue

The wind profile at a site determines the COE and the revenue to a wind farm operator by determining the number of kW h sold. Since wind power scales with the cube of wind velocity, the velocity of the air is likely to be the most important single factor in determining the placement of offshore wind farms and their profitability. The strongest winds offshore of the U.S. occur in the Aleutian Islands in Alaska, off the coast of northern California and southern Oregon, and in the Atlantic Ocean off the southern and eastern coasts of Massachusetts. In all of these places wind speeds at 50 m average 8.8–11.1 m/s [10]. While these are the largest concentrations of strong winds, there may also be areas of class 7 winds (the most powerful wind class, considered superb by NREL for energy production) at 80 m off the coasts of Texas, Louisiana, North Carolina and Long Island [27], however, these winds were not identified by some other studies [10].

The value of energy is also determined by the time of the day in which these winds blow. Electricity is not equally valuable throughout the day and developers interested in site selection need to know not just the mean annual wind speed, but the time of day and time of year in which the wind is strongest.

Revenue is determined by costs of energy at the local level. In the U.S. the average retail price of electricity ranges from 4.92 to 20.72 cents/kW h [28]. Thus an offshore wind farm may not be practical in Washington (average retail price of electricity is 6.14 cents/kW h) but may be very profitable in Hawaii where the average price is over 3 times higher (20.72 cents/kW h).

Revenue is also impacted by what other marketable products the wind farm generates. In states with Renewable Portfolio Standards (RPS), wind farm operators could sell renewable energy credits (RECs). States with RPS include most of the states with offshore wind potential with the exception of Ohio, Georgia, Louisiana and Michigan. The prices of RECs vary dramatically with the most expensive RECs being about $45 to $55/MW h in Massachusetts, Connecticut and Rhode Island.

The differences in local prices for electricity and RECs mean that the Cape Wind project may be able to sell its electricity for about 13 cents/kW h (average wholesale price of electricity in New England in 2007 was 7.7 cents/kW h; average REC price is 5.5 cents/kW h), while the Galveston Offshore Wind project may only be able to sell electricity at half that rate (average wholesale price of electricity in Texas in 2007 was 5.7 cents/kW h; average REC price is 0.5 cents/kW h; [22,28]). These differences in revenue could determine if a wind farm would be competitive with fossil-fueled fired electricity or not.

6.2. Site selection impacts

Previously, we discussed the possible impacts of water depth and distance to shore on capital costs, however, other factors associated with the site selection will also impact capital costs, for example, seafloor geology. Most offshore wind farms have been established using driven monopiles, however, monopiles are impractical in rocky soil since they may require drilling. Suction caissons have been employed as foundations for some turbines and they have been installed in both clay and sandy soils, but, firmer substrates require larger pressure difference between the outside and inside of the basket. Therefore, suction foundations may be impractical in some shallow water applications.

Areas with extreme weather events, and even areas with a high frequency of moderate weather events, can also influence costs. Moderate waves (above 2 m) can delay construction and effect the proportion of time that maintenance crews can access the turbines.

Hurricanes could dramatically influence the costs of construction and insurance. Current onshore towers are built to withstand 120 mph winds; hurricanes often have winds that significantly exceed this threshold. WEST, a company interested in building an offshore wind farm off the coast of Texas, has developed plans for a wind turbine that could withstand winds in excess of 150 mph [29]; it is unclear how much this might add to the cost of a turbine. Given the frequency of hurricanes in the Gulf of Mexico and the 20–30 year lifetime of a wind farm, it seems prudent for any wind farm to plan on being impacted by one or more hurricanes over its lifetime.

6.3. Project specific impacts

The costs of installation are partly determined by how many of the components are assembled on land. In some cases, developers have assembled components and even complete turbines on land and then shipped them to the installation site. This may decrease the time in which barges are needed but increase the sizes of the barges needed for construction. Barge costs are determined by the market; if wind farm development increases barge utilization then demand conditions will likely increase dayrates. Contracts with barges can be on either a turnkey or dayrate basis. Turnkey contracts transfer the operational risks associated with construction to the contractor; the party who holds weather related delay is determined by the terms of the contract.

6.4. Economies of scale

The largest wind turbines in the world are built by two German companies, Enercon and Repower. Enercon is building a 6 MW prototype land-based turbine while Repower sells a 5 MW turbine. Physical principles suggest that these larger machines should be more expensive per kW than smaller turbines because the material needed for a turbine should scale with the third power of rotor diameter while the power should scale with the square of rotor diameter [16,20]. However, empirical data suggest that the cost per kW of capacity has stayed relatively constant with increasing rotor diameter due to technological innovation [20] and the weight of the blades and the nacelles has scaled with the exponents 2.3 and 1.5 respectively, rather than the cube as expected [16]. This, combined with the fact that operation and maintenance costs are lower for wind farms with fewer, larger turbines, means that as the scale of wind farms increases, the costs of energy may decrease [30]. These cost reductions reach a limit for land-based wind farms due to the high costs of transporting huge turbines and blades. For offshore turbines transportation over roadways is not an issue, and it is likely that the size of offshore turbines may continue to increase above 5 MW [9]. We would expect that wind farms using large turbines would therefore be cheaper on a per kW capacity basis, but so far this has not occurred (Fig. 2).

We might also expect larger wind farms to be less expensive on a per MW basis than smaller wind farms [31]. This could occur through discounts with large turbine purchases, through learning associated with installation of foundations, through operation and maintenance efficiencies or through decreasing per MW electrical connection costs. However, neither the data for onshore wind farms seem to support this expectation [32] nor do the data for offshore wind farms (Fig. 3).

6.5. Technological learning

Musial and Butterfield [17] predicted that the COE for an offshore wind farm in shallow water would decline from $54/MW h in 2006 to $32/MW h 2025 based on technological learning and independent of cost reductions through scale economies.

There are several ways in which technological learning could take place; it could occur through incremental developments, the development of new main components, or through the development of entirely new turbine concepts [18]. Incremental development consists of developing new methods for turbine installation, advanced blade materials, easier access to the turbines, and more reliable electronic components, and is expected to be the major source of future price reductions[2] [18,33]. Other options for technological cost reductions include the use of DC transmission, the mass production of jacketed structures, and the assembly of turbine components onshore [16,18,33].

7. Environmental impacts of offshore wind power

Offshore wind power has both positive and negative environmental consequences. The negative environmental consequences are generally local, whereas the positive environmental consequences are global and exist only insofar as offshore wind power displaces other forms of electricity generation. The environmental impacts studied in the Cape Wind EIS are shown in Table 5, but note that the U.S. Fish and Wildlife Service has objected that the data used to make the determinations in the table were not adequate. In general, the environmental impacts of offshore wind are similar to those from onshore wind, however, offshore wind has additional environmental impacts, primarily associated with the effects of noise on marine animals, that onshore wind does not share.

7.1. Impacts on birds

One of the primary concerns surrounding wind farms is the risk that they will cause excessive avian mortality through collisions. The birds most at risk of collision will be seabirds, and in some cases migrating passerines. While bird mortality increases due to the risk of colliding with offshore turbines, the rate of mortality is relatively low, from 0.01 to 23 mortalities per turbine per year (these data are from both on and offshore wind farms; [34]). On a per MW basis, fatalities range from 0.95 to 11.67 deaths per year [35]. Altamont pass in California became notorious for its bird mortality. While the annual collision rate per turbine was low (0.02–0.15 collisions per year), mortality was still sizable due to the fact that 7000 turbines were involved and many of the birds killed were golden eagles, a charismatic species [34]. These data suggest that the fatality rate may be highly dependent on site specific factors.

The estimates above were generally taken from studies in which mortality was measured by counting dead birds found near turbines and, in some cases, correcting for birds removed by scavengers. In the offshore environment counting carcasses is likely to be very difficult due to the fact that many carcasses will not be found [36]. At Nysted, a thermal imaging system was placed on one of the turbines and could monitor 30% of the swept area for bird collisions. Using these data, it was predicted that approximately 0.02% of birds would collide with turbines.

Wind farms can also pose barriers to birds. Birds often seem to avoid flying through wind farms; this likely decreases their mortality [37]. However, birds that avoid a wind farm must expend a significant amount of energy flying around it, especially since offshore wind farms can be quite large (tens of square miles). This could be of particular importance if a wind farm is located in between rookeries and feeding grounds [34].

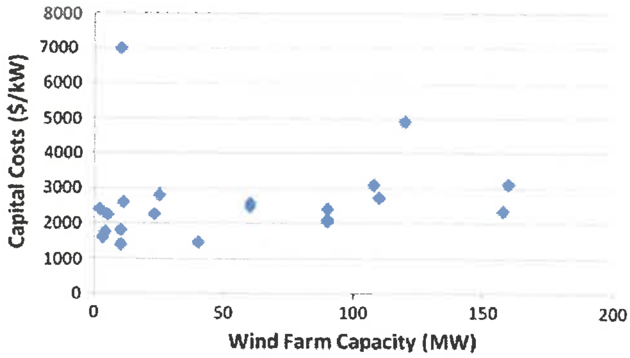

Fig. 3. Capital costs as a function of wind farm size.

Table 5
Environmental impacts associated with Cape Wind development according to the EIS.

	Affected resource	Construction impacts[a]	Operation impacts
Oceanography	Currents	No measurable impacts	Minor
	Waves	No measurable impacts	No measurable impacts
	Salinity	No measurable impacts	No measurable impacts
	Temperature	No measurable impacts	No measurable impacts
	Sediment transport	Minor	Minor
	Water depth	Minor	Minor
Birds	Raptors	No measurable impacts	No measurable impacts
	Passerines	Minor	No measurable impacts to Minor
	Coastal species	No measurable impacts to Minor	No measurable impacts to Moderate
	Marine birds	Minor to Moderate	Minor to Moderate
Invertebrates	Benthic invertebrates	Minor	Minor
	Shellfish	Minor	Minor
	Plankton	No measurable impacts	Minor
Fisheries	Finfish	Minor	No measurable impacts to Minor
	Demersal eggs and larvae	Moderate	
	Fish habitat	No measurable impacts to Minor	No measurable impacts to Minor
Marine Mammals	Marine Mammals	Minor to Moderate	No measurable impacts to Moderate
Endangered Species	Sea turtles	No measurable impacts to Minor	No measurable impacts to Minor
	Cetaceans	No measurable impacts to Minor	No measurable impacts to Minor
	Birds	No measurable impacts to Minor	No measurable impacts to Moderate

[a] Minor impacts are those that can be completely mitigated against or are small enough that the resource can recover completely on its own. Moderate impacts occur if either the impact is immitigable but the resource could recover on its own, or if the impact can be partially mitigated and the resource could then recover on its own. Major impacts occur if the impact is immitigable, the viability of the resource is threatened and the resource would not fully recover.

[2] One example of this could be the learning that occurred during the Horns Rev installation. Eighty turbines were installed at Horns Rev. At the start of construction the average installation time was 3 days; by the end of the construction period an average of 1.4 turbines was installed per day [16].

Finally, wind farms can remove essential habitat from seabirds. Many seabirds have restricted areas in which they can successfully feed and in many cases these areas are shallow sand banks appropriate for wind farm development. If birds avoid wind farms, then even though the footprint of a wind turbine foundation is very small, very large areas of habitat may be inaccessible to birds. This seems to have occurred among diving birds at the Horns Rev wind park and long-tailed ducks at Nysted wind park. Similar patterns are seen for terns and auks at Horns Rev, although the trends are not significant [38].

7.2. Impacts on marine mammals

Many cetaceans use echolocation to find food and many more communicate via acoustic signals. As a result many cetaceans, particularly porpoises, have very sensitive hearing which can be damaged by the loud noises associated with wind farms, particularly the sounds of pile driving. At the site of construction, the sound pressure level of pile driving a monopole for a 1.5 MW turbine is 228 dB [39]. Four-hundred meters away from pile driving the sound pressure level is 189 dB. This would cause hearing loss in seals. Hearing loss for porpoises would likely extend 1.8 km away from the source. Pile driving would be audible to porpoises and seals for at least 80 km and might cause behavioral responses up to 20 km away [39]. This sound pressure level is similar to, but slightly less intense than that used in naval sonar which has been implicated in the mass stranding of beaked whales [39]. During wind farm operation the noise from the turbines may be detectable for porpoises and seals up to about 1 km from the source [39].

At the Nysted Wind farm the population of harbor and grey seals was monitored before, during and after construction. Wind farm operation did not seem to significantly impact seal abundance, however, piling driving operations that occurred at one foundation site (Nysted uses gravity foundations) did decrease the number of seals observed at a nearby breeding site. Also, while the total annual population remained stable, after construction fewer harbor seals were present on nearby land sites in June (the breeding season) but more were present in July and August. This could suggest that fewer seals are using the area around the wind farm for breeding which could have an important effect on the viability of the population.

Harbor porpoises were shown to occur less frequently in the area around a wind farm during construction at both Nysted [40] and Horns Rev [38]. Presumably this is primarily due to animals fleeing the noise. At Horns Rev, the porpoises seemed to return following the construction period, however, even two years later porpoises at Nysted are less numerous then they were in baseline [38].

7.3. Impacts on fish

Wind farms could have both positive and negative impacts on fish. These effects could cascade up the food web to have either positive or negative effects on the birds and marine mammals that consume them.

As with marine mammals, fish can be very sensitive to loud sounds and could be displaced during wind farm construction; however, there is a great deal of variability among fish auditory systems and different species of fish will respond differently to noise from underwater construction. Furthermore, bottom-dwelling will be affected differently from fish swimming in the water column due to the different propagation of sound through sediment [39].

There have been few studies on the effects of pile driving on fish (reviewed in [41]). In general, these studies have placed fish in cages at various distances from the piles being driven and measured mortality and other injuries through non-microscopic necropsy. Abbott and Bing-Sawyer [42] studied Sacramento blackfish and found that fish placed in cages close to the sound source (45 m) experienced more damage than animals further away and that damage was only found in animals exposed to 193 dB or more. CALTRANS [43] studied shiner surfperch and steelhead and compared damage between fish experimentally exposed to pile driving and fish that were transported to the site but not exposed to noise. They found that fish exposed to pile driving noise experienced more damage than unexposed animals, but that there was no significant difference in mortality rates between control and experimental animals. CALTRANS [44] also conducted an observational study of fish mortality during pile driving for the San Francisco–Oakland bay bridge and found dead fish out to 50 meters around the construction. Finally, Abott [45] and Marty [46] studied the effects of a relatively small pile (2 feet in diameter) being driven close (32 feet) to cages of shiner perch, Chinook salmon and northern anchovies and they used control fish subjected to the same conditions but without noise. They found no difference in either mortality or pathology.

There have also been a few studies on the effects of noise on stress levels in fish. Chronic noise exposure is known to increase stress levels in humans with consequential effects on health. Smith et al. [47] studied the effects of a continuous 170 dB noise on corticosterone (a stress hormone) levels in goldfish and found no statistically significant results.

More subtle effects on fish behavior could also occur. Engas et al. [48] and Engas and Lokkeborg [49], found that the catch rate of haddock and cod decreased in areas after air gun use but returned to normal several days later suggesting that fish left the area and gradually returned. Nedwell et al. [50] calculated the zones around which salmon and cod would show significant avoidance behavior to be 1.4 km and 5.5 km, respectively.

The only clear conclusions which can be drawn from this research is that pile driving will effect fish; the degree of this effect will vary and is not at all clear. Very close to pile driving some mortality may occur for some species and fish may temporarily leave the area.

Many species of fish are also sensitive to electric and magnetic fields which can be caused by buried underwater cables. Fish use their perception of electric and magnetic fields for orientation and prey detection. Species that contain magnetic material, potentially for navigational purposes include several species of economically important fish including yellow fin tuna, and Chinook and sockeye salmon [51]. There is some evidence that the fish in the area of the Nysted wind farm may be affected by the electromagnetic fields produced by the wind farm. Baltic herring, common eels, Atlantic cod and flounder all showed asymmetries in the catch rate on either side of the cables suggesting that the cables may retard migration [38].

In addition to these negative effects, there has been some discussion of the potential for positive impacts from offshore wind farms on fish and fisheries. After construction of an offshore wind farm, turbine foundations could act as fish aggregating devices (FADs). The foundations could add three dimensional complexity to the environment and serve as a substrate for benthic invertebrates, thereby attracting fish. Offshore oil platforms are well known for this property. Although monopiles lack the structure of offshore oil and gas platforms, Wilhelmsson et al. [52] have shown that they act as fish aggregating devices at the Yttre Stengrund and Utgrunden wind farms. At the Horns Rev and Nysted wind farms there was no clear difference between fish densities inside and outside of the wind farms [38]. The difference in these results is likely due to the different methodologies employed. The Swedish studies used scuba divers to monitor fish while the Danish studies used hydro-acoustic sampling. As a result, the Danish studies may have overlooked some of the smaller species observed in the Swedish wind farms.

7.4. Environmental benefits of offshore wind power

Wind power is considered to be among the most environmentally benign sources of electricity available today and it is important to consider the negative environmental impacts of wind power in the context of alternative sources of electricity. For example, concerns about the impacts of wind power on birds should be compared to the impacts of fossil fuel use on birds on a per MW basis.

7.4.1. Greenhouse gases

The primary environmental benefit of wind power is its negligible contribution to global climate change. The only greenhouse gases produced by the establishment of a wind farm are those used in the construction and operation of the wind farm. The greenhouse gases released from construction and operation of an offshore wind farm are likely to be dominated by CO_2 released from the ships used in construction of the wind farm and the manufacturing of the steel used in the turbine towers and foundations. To our knowledge there is no estimate of these emissions for offshore wind farms, but for onshore wind farms these emissions decrease the CO_2 offset by 1–2% [53]. It is not clear whether offshore turbines would have higher or lower per MW CO_2 output from construction. In general, transportation via ship is more efficient than over land, but the operation and maintenance emissions may be higher for offshore wind. Assuming an offshore wind turbine replaces electricity generation from fossil sources at a rate equal to that for onshore wind farms, then each MW of wind capacity should displace about 1800 tons of CO_2 per year [54].

It is extremely difficult to predict the effects of climate change per ton of CO_2. While we can predict a per MW bird mortality associated with wind power, we cannot make a comparable prediction for fossil fuel use. Studies have indicated that climate change may be associated with high rates of species extinction. Climate change is predicted to cause between 11 and 45% of all species to become extinct [55]. For birds, the subject of so much concern over wind power, it is estimated that 950–1800 species of terrestrial birds (out of 8750 studied) will be threatened due (in part) to climate change [56]. It is critically important, however, that there has been very few studies of the adaptation of biodiversity to climate change, thus these estimates must be taken as preliminary [57]. Still, the fact that climate change may imperil the survival of species, especially species endemic to high and low altitudes and latitudes and restricted geographical ranges, is in contrast to wind power which has no demonstrated population or species level effects on biodiversity.

7.4.2. Water

In many parts of the U.S. water resources are stressed. The six world climate models used in the Intergovernmental Panel on Climate Change (IPCC) generally predict that the U.S. will become drier by 2050. One of the models predicts that precipitation over virtually the entire U.S. will decline by over 30% while the other five models show more modest declines [57]. Forty-eight percent of total water withdraws and nine percent of total water consumption (68 billion liters per day) is used by thermoelectric power plants (powered by coal, natural gas, nuclear, oil and biomass; [9]). Ethanol production also uses large quantities of water, from 3.5 to 6 l of water for every liter of ethanol produced [58]. Wind power directly uses no water. Per kW h, the amount of water used in fossil-fueled plants ranges from about 0.2 to 0.6 gallons depending on the technology employed [59]. Assuming a 40% capacity factor, 1 MW of offshore wind power can offset the use of between 0.7 and 2.1 million gallons of freshwater per year.

7.4.3. Value of ecological benefits

Onshore and offshore wind have nearly identical ecological benefits on a per MW h basis. We can attempt to place a dollar value on the ecological services, in terms of water unused and carbon not emitted, of offshore wind power relative to traditional fossil-fueled power. The actual costs of offsetting a ton of carbon are not known, but governments have set up trading systems in which offsets are exchanged. The costs of these offsets will be set by supply and demand, and are expected to increase in the future. Current prices for the offset of one metric ton of CO_2 are around $30. Each MW h of coal-fired electricity produces 0.839 metric tons of CO_2 [60]. Thus, per MW h, the value of avoided CO_2 emissions may be about $25.

8. Ecological mitigation

8.1. Mitigation through site selection

Potential sites are avoided due to their potential impacts on the environment. Certain areas are known to be bottlenecks on the migratory routes of large numbers of birds. Cape May, New Jersey, Delaware Bay, Grays Harbor Washington, Point Reyes, California, and the Barrier Islands of Louisiana are all important areas for avian migration and may be considered unacceptable for offshore wind power development. Similarly, planners for the LIOWP took the migration routes of Right Whales into consideration in selecting a site. Whale migration routes will likely need to be considered on the Pacific coast as well.

Placing offshore wind farms near nesting sites for seabirds may also be ecologically hazardous. Seabirds generally avoid using the Horns Rev wind farm and direct mortality from collision with turbines is relatively rare and in many cases not significant. However, because seabirds avoid entering offshore wind farms, their existence may reduce available foraging habitat or force birds to expend energy to fly around the wind farm. Both of these could have population level impacts on bird species. Offshore wind farm construction could also have similar impacts on nearby populations of marine mammals.

From the perspective of conserving biodiversity, it is perhaps most important for developers to avoid areas considered essential habitat for threatened or endangered species. The endangered species act requires that critical habitat for any listed species be identified and it requires federal agencies that permit activities consider the effects of permitting on these habitats. While there are procedures in which the government may permit activities that are detrimental to the critical habitat of an endangered species, it would seem prudent for developers to exclude critical habitats of endangered species from development plans, if not out of a perceived ethical responsibility for conservation, then out of the risk of the failure of the permitting process and the associated financial losses.

The areas of critical habitat for species managed by NOAA are listed at http://www.nmfs.noaa.gov/pr/species/criticalhabitat.htm and species managed by FWS are listed at http://crithab.fws.gov/. The critical habitat of the North Atlantic Right Whale and the Stellar Sea Lion, both managed by NOAA, are the most likely to influence offshore wind placement. The critical habitat of the North Atlantic Right Whale includes areas off the coast of southern Georgia and the Atlantic Coast of Northern Florida as well as areas off the Northern and Eastern coasts of Cape Cod. The areas of critical habitat that may conflict with offshore wind power development for the Stellar's sea lion consist of five small zones off the coast of northern California and Oregon.

The impacts on local culture should also be considered. One of the primary criticisms of the Cape Wind project is that it will spoil the views from historic areas. Similarly, some areas of interest for offshore wind development may be located near shipwrecks. These issues should be noted by wind power developers for two reasons. First, the MMS, in their guidelines on development of the OCS, adopted a policy of consulting with State Preservation Authorities before permitting development and it is therefore possible that MMS would decline a permit for offshore wind energy if there were significant cultural issues. Secondly, even if MMS were to allow development, construction can be seriously slowed by local community resistance. For example, the Cape Wind project will, if completed, have taken at least a decade to develop and have required at least one protracted legal battle (*Alliance to Protect Nantucket Sound v. United States Army*). In contrast, WEST's plans to build a wind farm off the coast of Texas have proceeded rapidly, despite less favorable wind conditions. This may be due to acceptance by the local community, many of whom are familiar with offshore structures from experience with the oil and gas industry [13].

8.2. Mitigation through technology

Most of the offshore wind turbines constructed to date have used monopole foundations. The ecological effects of the piling operations are a concern, however, there are alternavites to pile-driven foundations. One option would be to use gravity foundations, as were used in the Nysted and Middlegrunden wind farms. Gravity foundations are simple concrete structures with large diameter bottoms that rest on the sea floor. They weigh thousands of tons and use their weight to stabilize the turbine. Gravity foundations do not require piling operations and therefore have less potential to disturb marine mammals and fish. Also, gravity foundations have more three dimensional structure than monopiles; this may provide additional habitat for benthic organisms.

Another alternative would be to use suction foundations, such as those considered in the Beatrice demonstration project. Suction foundations are simple steel baskets that are placed on the seafloor and form a seal with the ocean bottom. Suction is then applied to the inside of the basket and the resulting pressure difference causes the basket to bury itself in the sediment, much like a driven monopile. Again, installation is much quieter allowing for fewer environmental effects.

Technologies are also being developed to allow the use of deeper water. Using deeper water would allow offshore wind farms to be sited further from shore, increasing the wind speed and decreasing the possibility of conflicts with local human and animal populations. A survey conducted in New Jersey showed visitors and residents simulated images of offshore wind farms at varying distances from shore and found that as the distance increased the percentage favoring development increased [61]. Deep water turbines could be placed over the horizon and thus be invisible from shore. This would also decrease their impact on seabirds which generally do not feed in the open ocean, and on migratory birds, which, with the exception of birds flying over the GOM, do not migrate over open ocean. Additionally, these turbines are placed on floating foundations that will likely have fewer environmental impacts during construction.

One of the leading developers of floating foundations for offshore wind turbines is Blue H Technologies. They have recently installed an offshore wind turbine in 108 m of water 20 km off the coast of Italy and also applied to MMS for a permit to study the potential for a wind farm 23 miles off the southern coast of Cape Cod. If this technology becomes economically viable it could decrease conflicts with coastal communities and would lessen the environmental impacts of wind farms.

9. Conclusion

The higher economic costs of offshore wind power relative to onshore wind power could be justified if the ecological or social costs of offshore wind were significantly different from onshore wind power, but this seems not to be the case. Both on and offshore wind power face local opposition due to user conflicts. The ecological impacts of offshore wind power affect a very different ecosystem than onshore wind power and, as a result, their ecological impacts are not directly comparable. However, like onshore wind, it is clear that offshore wind power does have ecological impacts with the potential for population level effects.

Decreasing commodity costs or legislation capping greenhouse gas emissions could increase the profitability of offshore wind but would not change the fact that onshore wind will be a less expensive alternative, even when transmission costs are included. Until land use conflicts in high-wind onshore sites become severe, or the technology develops so that the higher offshore winds balance the higher costs of installation, there seems to be little incentive for a large offshore wind industry in the U.S. In sum, we do not envision offshore wind producing a significant portion of the U.S. electricity production until at least 2020.

It is much more difficult to analyze the ecological and economic costs and benefits of offshore wind power relative to fossil-fueled power. Including a premium on coal-fired power of $25/MW h to offset emissions may make coal and offshore wind power nearly price competitive, depending on the specific capital costs of offshore wind. This $25/MW h premium would give coal and offshore wind similar greenhouse gas emissions, however, coal would still use more water than offshore wind and would be associated with significant health effects. However, this would be balanced against the ecological impacts of offshore wind in terms of bird and bat mortality and marine mammal impacts. Thus, it is not clear that offshore wind is preferable to coal-fired power, if the emissions from the coal plant are offset.

Based on the analysis in this paper, it seems clear that the economic and ecological costs of offshore wind power are site specific. These costs can be mitigated with current technology and detailed site selection. It therefore seems imprudent to conclude that all offshore wind development is inferior to all onshore wind development or fossil-fueled power. Instead, a more nuanced approach which weighs the site specific costs and benefits of offshore wind power is necessary. In some cases, offshore wind power may be able to cheaply produce electricity with negligible environmental impacts, however, in many more cases, offshore wind power will be more expensive than its competitors, even when the costs of carbon offsets are included.

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