Valuing Offshore Wind Energy

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1 Introduction

The U.S. Department of Energy and the Commonwealth of Massachusetts have set ambitious goals for offshore wind energy development (An Act to Promote Energy Diversity, 2016; U.S. Department of Energy, 2016). Offshore wind energy can contribute to mitigating climate change, but addressing concerns about local ecosystem impacts are central to the permitting process. The Bureau of Ocean Energy Management (BOEM) coordinates with the U.S. Fish and Wildlife Service and other agencies in data collection and assessment for offshore wind farm permitting. Coastal waters provide critical habitat for threatened and endangered species as well as the livelihood of many coastal residents. These critical ecosystems are at risk from the impacts of climate change and potentially from offshore wind farms. Therefore, we need a way to compare the potential impacts of offshore wind energy development on local ecosystems and on climate change. This paper provides a model for thinking about the global value of offshore wind energy in terms of its potential to contribute to climate change mitigation. Local and regional decision makers can then compare the global value with the local impacts to make trade-offs appropriate for their community.

To estimate the value of offshore wind energy, we incorporate offshore wind energy into an integrated assessment model (IAM), the Global Change Assessment Model, USA version (GCAM-USA). The GCAM-USA model is a global model which models each state in the US in addition to the other 31 global regions considered in the release version. It couples energy technologies with the economy, land use, and the climate (Joint Global Change Research Institute, 2016; Pacific Northwest National Laboratory, 2016). GCAM can estimate the cost of abatement and the global mean temperature change under different conditions. Damage functions convert temperature change into monetary damages over the rest of the century. Across a range of policy cases, we look at how changes in the cost of abatement and the cost of damages contribute to the total value of permitting offshore wind energy over the rest of the century. We note that we use the word "permitting" in both of its senses: permitting as in allowing, and permitting as the process of issuing permits for construction.

The next section describes how we model the value of offshore wind energy in the context of climate change. Section 3 describes the data and methods used to generate our estimates. Specifically, we discuss the creation of the offshore wind energy supply curves and the damage functions used. Section **??** describes the results and Section **??** concludes.

2 The value of offshore wind energy: Conceptual model

The net environmental value of a technology, as we define it, is related to the total cost of climate change, which is composed of two main factors: the cost of abatement and the level of climate damages. Define ϕ as the climate policy, ψ as a set of parameters such as the cost trajectory of offshore wind energy or the exponent of climate damages, and R as the set of available energy generating technologies. Let $TC(\phi, \psi, R)$ be the total cost from climate change, including the cost of reducing emissions and the cost of damages caused by climate change. The value of permitting offshore wind energy is $V(\phi, \psi) = TC(\phi, \psi, R^0) - TC(\phi, \psi, R^w)$, the difference in the total costs of climate change without and with offshore wind energy, respectively.

We focus on two endogenous variables that are the outcome of a decision process, typically an optimization, but we also leave open the option of other decision processes, such as satisficing. These are abatement, representing an abatement path, $\mu^*(\phi, \psi, R)$, and the portfolio of energy generation, $S^*(\phi, \psi, R)$, defined as the time path of the amount of energy generated from different technologies. Abatement is the fraction of emissions reduced below a "business as usual" (BAU) level. In a BAU case, there is no explicit climate policy. For example, if the policy ϕ is BAU and we have baseline technologies, R^0, then we define abatement μ^* to be zero. If the policy ϕ is a carbon tax, then μ^* is the level of abatement that arises in the economy for the specified level of the tax.

The cost of abatement depends directly on the amount of abatement, the portfolio of energy technologies, and other parameters, $C(\mu, S, \psi)$. The damages from climate change depend on the abatement and other parameters, $D(\mu, \psi)$. Other parameters include, for example, the costs of technology for offshore wind farms and parameters of the damage function.

$$TC(\phi, \psi, R) = C(\mu^*(\phi, \psi, R), S^*(\phi, \psi, R), \psi) + D(\mu^*(\phi, \psi, R), \psi) \qquad (1)$$

Define $\mu^0 \equiv \mu^*(\phi, \psi, R^0)$, where R^0 does not include offshore wind. Define $S^0 \equiv S^*(\phi, \psi, R^0)$, similarly. Now, consider the case where wind is permitted; define $\mu^w \equiv \mu^*(\phi, \psi, R^w)$ and S^w similarly. From here on, we write only μ^0, μ^w, S^0 or S^w and suppress ϕ, ψ, and R in these endogenous variables. The value of permitting offshore wind energy is:

$$V(\phi, \psi) = \left[C(\mu^0, S^0, \psi) + D(\mu^0, \psi)\right] - \left[C(\mu^w, S^w, \psi) + D(\mu^w, \psi)\right] \qquad (2)$$

where the endogenous variables depend on ϕ, ψ and R as discussed above.

Depending on the climate policy, this value, V, derives from different components of Equation 2. Rearranging this equation shows the value as the sum of the change in the cost of abatement and the change in the cost of damages.

$$V(\phi, \psi) = \left[C(\mu^0, S^0, \psi) - C(\mu^w, S^w, \psi)\right] + \left[D(\mu^0, \psi) - D(\mu^w, \psi)\right] \qquad (3)$$

Further rearranging gives the following equation, showing that the value is the sum of the reduced cost of abatement resulting from the change in technology availability for a given level of abatement, in the first term, and the net value resulting from the change in abatement, in the second term.

$$
\begin{aligned}
V(\phi, \psi) = & \big[C(\mu^0, S^0, \psi) - C(\mu^0, S^w, \psi)\big] + \\
& \Big\{\big[C(\mu^0, S^w, \psi) - C(\mu^w, S^w, \psi)\big] + \big[D(\mu^0, \psi) - D(\mu^w, \psi)\big]\Big\}
\end{aligned}
\tag{4}
$$

The first term in square brackets represents the change in the cost of a fixed level of abatement due to the introduction of offshore wind. The second term, in curly brackets, represents the change in costs due to changing the level of abatement. The first term within this term is the change in abatement costs, the second term is the change in damage costs. Note that if offshore wind is a low cost option for abatement and if abatement is responsive to costs, we would expect the first term to be positive; the first part of the second term to be negative, and the second part of the second term to be positive.

In the case of a BAU policy, with no pricing of carbon or limits on carbon emissions, we assume that offshore wind is used only if it is economical to do so. Therefore, we assume that the overall cost of abatement will not change: $C(\mu^0, S^0, \psi) - C(\mu^w, S^w, \psi)$ will be equal to zero in this case. It could, however, reduce the cost of damages if it displaces fossil fuel generation and lowers emissions. Thus:

$$V(BAU, \psi) = D(\mu^0, \psi) - D(\mu^w, \psi)$$

In the case of an emission cap, permitting offshore wind projects will not change the level of abatement, which is defined by the policy; however, it could reduce the cost of abatement if offshore wind energy is a less expensive abatement option.

$$V(Cap, \psi) = C(\mu^0, S^0, \psi) - C(\mu^0, S^w, \psi)$$

Under a carbon tax policy, the value of offshore wind energy is derived from both the change in the cost of abatement as well as the change in the cost of damages (Eq. 3). In this case, we can choose both the level of abatement and the energy generation portfolio.

We use this conceptual model to estimate the value of offshore wind across a range of climate policy scenarios and offshore wind technology cost scenarios. The next section describes the data sources and the calculations required to generate these estimates.

3 Data and calibration of computational models

To estimate the monetary value of the abatement and damages in Equation (2), we use the Global Change Assessment Model USA version (GCAM-USA). The GCAM-USA takes information on energy technologies, socioeconomic data, and policies and calculates cost minimizing abatement and energy generation. From the GCAM-USA we can collects outputs for the CO2 emissions and a temperature path, which can then be used to calculate the cost of abatement and the damages, respectively. The current standard version of GCAM-USA contains a model for onshore wind. For this work, we created a new version which also includes a model for offshore wind, GCAM-USA-OWE. This model will be submitted for inclusion in future releases of GCAM. Section 3 explains our model for offshore wind in detail.

GCAM has contained a model of onshore wind for a long time, but we developed the model for offshore wind for this paper. In order to model offshore wind, GCAM requires supply curves for each region, a time path of technology costs and technology selection parameters. Supply curves provide estimates of how much energy is available at different costs in a state or region. Section 3.1 details the development of these supply curves from technology cost data and the characteristics of offshore space. This section also describes the data on how the cost of offshore wind technologies might change over time.

Once we have offshore wind data included in GCAM-USA-OWE, we can use the CO2 emissions and temperature change outputs of the model to estimate the value of offshore wind. Section 3.2 describes how we calculate the cost of abatement from the CO2 emissions pathways. Section 3.3 discusses how we estimate damages given a temperature path.

3.1 Supply curves

The amount of energy available depends on the typical wind speeds in that area. The cost of energy depends on the wind speeds, water depth, and

Table 1: Summary of wind farm characteristics.

Characteristic	Value	Source
Turbine Size	5 MW	Schwartz et al., 2010
Wind Farm Size	500 MW	Myhr et al., 2014
Density of Capacity	5.0 MW/km^2	Schwartz et al., 2010
Weibull k Factor	2.1	Myhr et al., 2014
Lifetime	30 years	Joint Global Change Research Institute, 2016; Pacific Northwest National Laboratory, 2016
Capital Recovery Factor	0.13	Joint Global Change Research Institute, 2016; Pacific Northwest National Laboratory, 2016

distance from shore. Using data from NREL (Beiter et al., 2016; Green et al., 2007; Mone et al., 2015) and Europe (Bjerkseter and Ågotnes, 2013; Myhr et al., 2014), we estimate the cost of offshore wind energy in different locations, in the U.S. and around the world, in low and high cost cases.

To develop resource supply curves, we make a number of assumptions about the characteristics of a "typical" wind farm based on previous work and summarized in Table 1. The capital recovery factor implies a discount rate of 12.6% with a 30 year lifetime. We have a range of values for different components of an offshore wind farm from the literature, shown in Table 2 and Figure 1. From these values, we create a high cost and a low cost case. Then we estimate the capital cost of offshore wind energy over a range of water depths and distances from shore. Figure 1 shows how the capital costs

Table 2: Low and high cost component estimates.

Cost Component	Low Value ($/kW)	High Value ($/kW)	Source
Turbine	1583	1988	Beiter et al., 2016; Myhr et al., 2014
Development and Consenting	196	277	Beiter et al., 2016; Myhr et al., 2014
Decommissioning	85	115	Beiter et al., 2016; Bjerkseter and Ågotnes, 2013; Mone et al., 2015
Other	678	678	Mone et al., 2015
Substructure (30m)	638	1031	Mone et al., 2015; Myhr et al., 2014
Substructure (45m)	846	1365	Mone et al., 2015; Myhr et al., 2014
Substructure (>60m)	1995	1995	Myhr et al., 2014

increase with depth and distance. With increasing distance, the costs increase with the additional length of export cable required. As depth increases, the cost of the fixed bottom foundation increases rapidly until it becomes necessary to switch to a floating concept.

We also model how costs change over time, shown in Figure 2. The baseline case matches the existing trend for onshore wind energy in GCAM. The advanced technology case follows the 5% annual decrease suggested by NREL until 2030 (Beiter et al., 2016) and then continues to decrease by 1% annually, consistent with Wiser et al. (2016).

Each state in the U.S. and each country around the world has a certain amount of area available at different distances from shore, water depths and

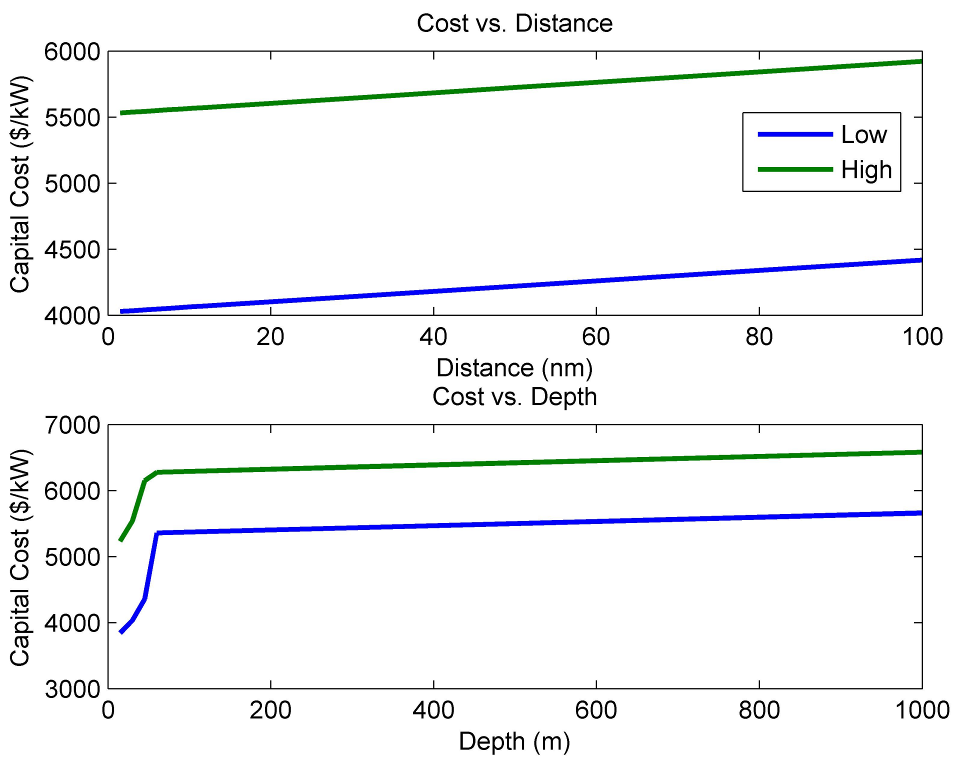

Figure 1: How capital costs change with distance from shore and water depth; top panel holds depth constant; bottom panel holds distance constant.

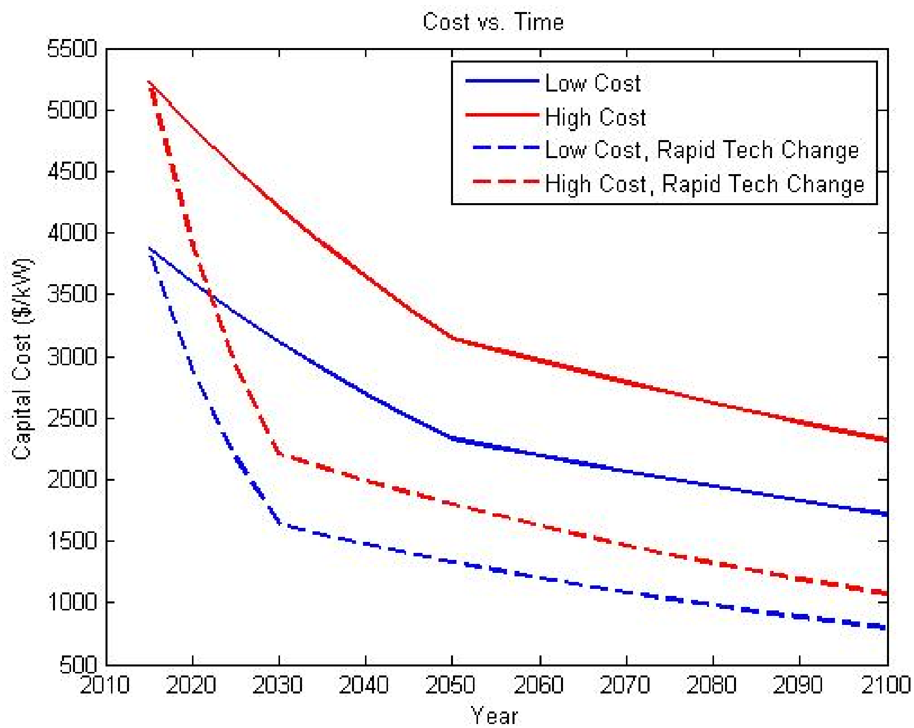

Figure 2: Trend in capital costs over time for low and high costs cases and rapid technological change cases.

wind speeds (Eurek et al., 2016; Musial et al., 2016; Schwartz et al., 2010). In the high cost case, we use the upper value in each range for depth and distance from shore and the lower value for wind speed. Conversely, in the low cost case, we use the lower value for depth and distance and the upper value for wind speed. This creates two bounding cases for cost of energy; one with higher costs and lower energy production and one with lower costs and higher energy production.

Using the cost and energy data, we calculate the levelized cost of energy (LCOE) as follows

$$\text{LCOE(distance,depth,wind speed)} = \frac{(\text{CapEx(distance,depth)} * \text{CRF} + \text{O\&Mfixed(depth)})}{(\text{CF(wind speed)} * 8760)}$$

The term CapEx(distance,depth) is the capital cost of offshore wind energy as a function of distance from shore and water depth in $/kW. O&Mfixed(depth) is the operations and maintenance cost as a function of water depth in $/kW. CF(wind speed) is the capacity factor as a function of the wind speed. The value 8760 is the number of hours in a year. The range of LCOE that we calculate for 2015 matches that in Beiter et al. (2016). Each area in Table 2 is assigned an LCOE and is ranked from low to high values to create a supply curve for offshore wind energy. We use two bounding cases with high costs and low energy and low costs and high energy as high and low cases respectively. Figure 3 gives some examples of offshore wind energy supply curves in the US. The state of Massachusetts has some of the least expensive offshore

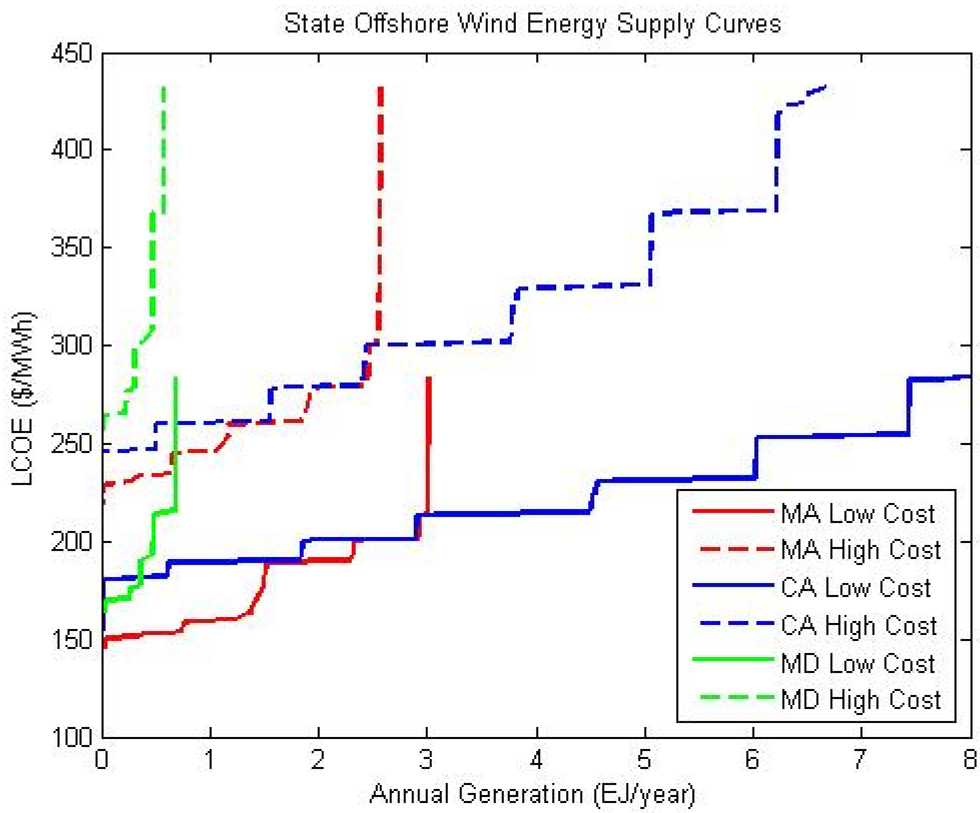

Figure 3: Supply curves from high and low cases in Massachusetts, California, and Maryland.

wind resources due to its high wind speeds and relatively shallow waters close to shore. California also has high wind speeds, but deeper water making offshore wind energy more expensive than in Massachusetts. California has more energy available because it's a larger state with more coastal area than Massachusetts. Maryland has lower wind speeds than Massachusetts, making it more expensive because much less energy available.

Supply curves for the states in the U.S. and for regions around the world are incorporated into the GCAM-USA model along with the assumptions about technological change and climate policies. The outputs from GCAM include the emissions pathway and the mean change in global temperature. The next section describes how the cost of abatement is calculated from the emissions and carbon tax pathways.

3.2 Cost of Abatement

In this section, we discuss how to estimate the cost of abatement based on the output from GCAM. First, we estimate a marginal cost of abatement and then use that to calculate the total cost of abatement. The marginal cost of abatement (MAC) refers to the cost of reducing emissions by one more ton. We estimate the MAC from GCAM by identifying the level of emissions in response to different levels of a carbon tax. According to economic theory, the economy will choose a level of emissions such that the marginal cost of reducing emissions is just equal to the carbon tax (Jehle and Reny, 2011; Varian, 1992). This provides a reasonable estimate of the MAC. The MAC curve is the derivative of the overall cost of abatement. Thus, we can estimate the cost of abatement as the area under the MAC curve (Barron et al., 2014).

We run GCAM with a range of carbon tax pathways to find the emissions pathway that results in each case. Using the carbon tax and the resulting reduction in emissions for each technology cost case, we estimate the marginal abatement cost curves shown in 4. In each time period, we compare the reduction in emissions with the range of carbon tax values applied in that time period. For example, in 2085 with the lowest cost offshore wind technology, with a carbon tax of \$100 per ton of carbon the economy abates 33% of emissions relative to a BAU case without any offshore wind energy. The marginal cost reducing one more ton of carbon is \$100. To estimate the cost of abatement, we convert the level of abatement into emissions relative to a BAU case. For the lowest cost offshore wind technology in 2085 with a carbon tax of 250 \$/TC the cost of abatement is 2 trillion 2015\$.

We use several points to calculate the marginal cost of abatement because we expect the first emissions reductions to be relatively inexpensive, but additional reductions to be increasingly expensive as it becomes more difficult. In other words, the marginal cost of abatement is an increasing function. The marginal cost of abatement shifts and pivots as the cost of offshore wind energy decreases.

The total cost of abatement is the present value of the cost of abatement over the rest of the century

$$C(\mu, S, \phi) = \sum_{t} n_t * \frac{C_t(\mu, S, \phi)}{(1+r)^{t-t_0}} \tag{5}$$

where t is the time period, n_t is the number of years in time period t, r is the discount rate, and t_0 is the reference year. To combine the cost of abatement with the change in temperature, temperature must be converted into a monetized value through a damage function as described in the next section.

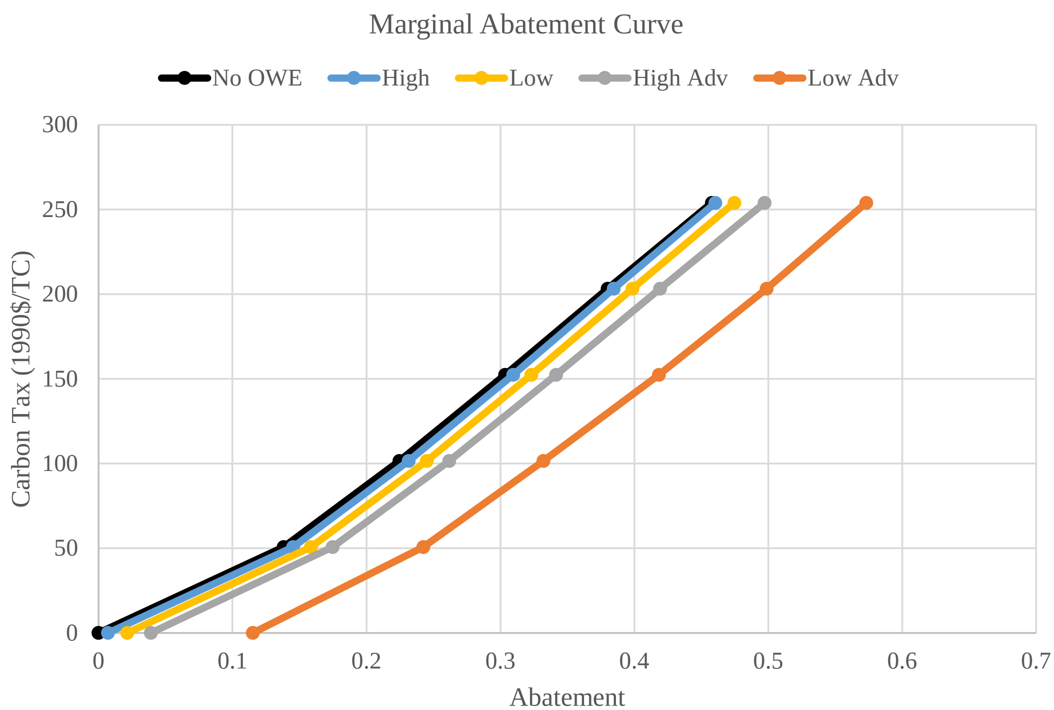

Figure 4: Marginal abatement cost curves.

3.3 Damages

We need to estimate the cost of damages associated with climate change, which is part of the value of offshore wind energy. Previous work (Hope, 2011; Nordhaus and Sztorc, 2013) has used damage functions which convert changes in the temperature into losses in gross domestic product (GDP). We use a range of damage functions since there is uncertainty over the impacts of climate change. Some integrated assessment models such as DICE (Nordhaus and Sztorc, 2013) and PAGE (Hope, 2011) use damage functions of the form

$$D_t(\Delta T_t) = a(\Delta T_t)^b.$$

where ΔT is the change in global mean temperature, a is a calibrated parameter, and b is a parameter for the severity of damages. The DICE model uses a value of b equal to two, which we take as a central case. The PAGE model uses values as low as 1.5 and as high as 3, which we take as low and high damage cases, respectively. The parameter a is calibrated to 0.00267, meaning that one degree Celsius increase of global mean temperature reduces global world product (GWP) by 0.267% (Nordhaus and Sztorc, 2013).

As with the cost of abatement, the total cost of damages in particular scenario is the present value over the rest of the century

$$D(\mu, \phi) = \sum_t n_t \, GDP_t \, \frac{D_t(\Delta T_t(\mu, \phi))}{(1+r)^{t-t_0}} \tag{6}$$

where GDP_t is the gross domestic product in time period t.

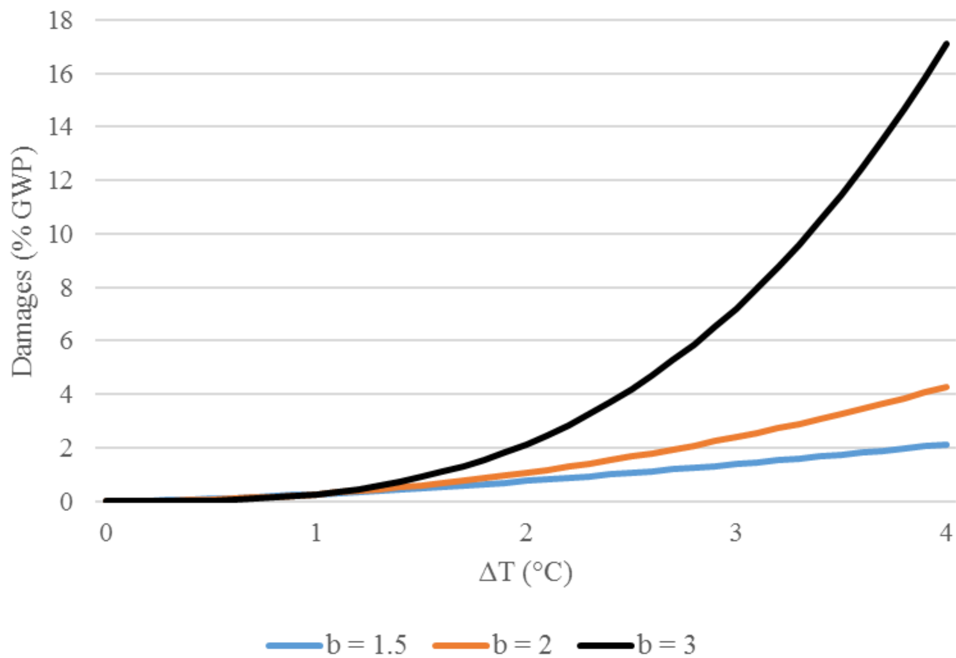

Figure 5: Damage functions used to estimate the monetary value of climate damages by converting global mean temperature change into a percent loss of GWP.

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A Supply curve data

To create the offshore wind energy supply curves for each state and region, we take the area data provided in Schwartz et al. (2010) and Eurek et al. (2016) and convert it into annual energy and LCOE. Each area has a range of wind speeds, water depths and distances from shore. We create high and low estimates of energy and LCOE based on the high and low ends of the ranges of these values. For instance, in the first cell of Table 3, the wind speeds are 7.0-7.5 m/s, the depth is 0-15m, and the distance is 0-3nm. To calculate the high cost offshore wind energy case, we take the high estimates of capital and O&M costs for 15m and 3nm and estimate the annual energy production based on 7.0 m/s. The table below shows all of theses high cost offshore wind energy estimates for Massachusetts. The top number is the area, the middle number is the estimated annual energy, and the bottom number is the estimated LCOE for that area.

Table 3: Area in Massachusetts at different distances from shore, water depths and wind speeds (Schwartz et al., 2010), low estimates of energy generation, and high estimates of LCOE as calculated in this paper.

		Area (km^2) (Energy (EJ)) (LCOE($/MWh))						
		Wind Speed (m/s)						
Distance	Depth	7.0-7.5	7.5-8.0	8.0-8.5	8.5-9.0	9.0-9.5	9.5-10.0	>10.0
0-3nm	Shallow 0-30m	201.6 (0.0086) (368.3)	521.4 (0.0253) (323.7)	927.4 (0.0502) (290.3)	1508.2 (0.0895) (264.7)	1137 (0.0729) (244.9)	2 (0.0001) (229.3)	0 (0) (217.0)
	Trans 30-60m	0 (0) (417.9)	4.7 (0.0002) (367.3)	327.3 (0.0177) (329.4)	378.1 (0.0224) (300.4)	322.6 (0.0207) (277.9)	0 (0) (260.2)	0 (0) (246.2)
	Deep >60m	0 (0) (422.1)	0 (0) (371.0)	28.6 (0.0015) (332.7)	12.6 (0.0007) (303.4)	20 (0.0013) (280.7)	0 (0) (262.8)	0 (0) (248.7)
3-12nm	Shallow 0-30m	0 (0) (370.2)	0 (0) (325.4)	78.2 (0.0042) (291.8)	315 (0.0187) (266.1)	2696.9 (0.1730) (246.2)	8.6 (0.0006) (230.5)	0 (0) (218.1)
	Trans 30-60m	0 (0) (419.8)	0 (0) (368.9)	152 (0.0082) (330.9)	354.5 (0.0210) (301.8)	1418.6 (0.0910) (279.1)	119.2 (0.0082) (261.4)	0 (0) (247.3)
	Deep > 60m	0 (0) (424.0)	0 (0) (372.7)	125.5 (0.0068) (334.2)	812.2 (0.0482) (304.8)	1006.5 (0.0646) (282.0)	0 (0) (264.0)	0 (0) (249.8)

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		Area (km^2) (Energy (EJ)) (LCOE($/MWh))						
		Wind Speed (m/s)						
Distance	Depth	7.0-7.5	7.5-8.0	8.0-8.5	8.5-9.0	9.0-9.5	9.5-10.0	>10.0
12-50nm	Shallow 0-30m	0 (0) (378.5)	0 (0) (332.6)	0 (0) (298.3)	11.4 (0.0007) (272.1)	1689.9 (0.1084) (251.7)	472.1 (0.0323) (235.7)	0 (0) (223.0)
	Trans 30-60m	0 (0) (427.9)	0 (0) (376.1)	0 (0) (337.3)	23.5 (0.0014) (307.6)	5051.8 (0.3241) (284.5)	3459.5 (0.2370) (266.4)	0 (0) (252.1)
	Deep >60m	0 (0) (432.2)	0 (0) (379.8)	0 (0) (340.6)	190.4 (0.0113) (310.6)	7007.4 (0.4495) (287.4)	9612.5 (0.6585) (269.1)	0 (0) (254.6)
	Total	201.6 (0.0086)	526.1 (0.0255)	1639.1 (0.0887)	3606 (0.2140)	20350.7 (1.3055)	13674 (0.9368)	0 (0)