Environmental Research Letters

PAPER • OPEN ACCESS

The global climate value of offshore wind energy

To cite this article: Alexana Cranmer and Erin Baker 2020 *Environ. Res. Lett.* **15** 054003

IOP Publishing Environ. Res. Lett. 15 (2020) 054003 https://doi.org/10.1088/1748-9326/ab7667

Environmental Research Letters

OPEN ACCESS

RECEIVED
27 August 2019

REVISED
12 February 2020

ACCEPTED FOR PUBLICATION
14 February 2020

PUBLISHED
23 April 2020

PAPER

The global climate value of offshore wind energy

Alexana Cranmer[1] and **Erin Baker**[2]

[1] Natural and Applied Sciences, Bentley University, 175 Forest Street, Waltham, MA 02452, United States of America
[2] Mechanical and Industrial Engineering, University of Massachusetts, 160 Governors Drive, Amherst, MA 01003, United States of America

E-mail: acranmer@bentley.edu

Keywords: offshore wind, climate change, integrated assessment, abatement

Supplementary material for this article is available online

Abstract

We estimate the climate value of offshore wind energy with a highly flexible, forward-looking method that estimates the value in a consistent manner under a range of policies, including carbon caps and taxes. Backward looking methods measure the damages avoided due to emissions reductions attributed to renewable energy under an existing policy structure. Under a carbon cap, however, the climate value of offshore wind energy comes entirely from reducing the cost of meeting the cap. Our method for estimating the prospective climate value compares both *climate damages* and *abatement costs* in cases with and without offshore wind energy. This climate value can be compared to the costs of reducing barriers to new technologies, such as streamlining approval processes. The climate value depends on the cost of offshore wind technology, the climate policy under consideration, the severity of damages from climate change, and the discount rate. In the absence of a binding climate policy, the climate value of offshore wind energy ranges from $246 billion to $2.5 trillion under central assumptions about damages and discount rate, and can reach over $30 trillion under certain assumptions (low discount rate, high damages, low technology costs). The value of technical change—of moving from the highest cost to lowest cost assumptions about the technology—is estimated to be $300 billion even under the most unfavorable assumptions, dwarfing worldwide R&D investment in *all* wind energy technology. Using this method, we find that new low carbon technologies can provide a hedge against uncertainty and error in climate policies.

1. Introduction

Offshore wind energy is an emerging industry that has the potential to provide large amounts of electricity near load centers where land is scarce [1]. Costs have been dropping in recent years [2] and are expected to continue falling [3–5]. Offshore wind has the potential to play an important role in reducing greenhouse gas emissions by replacing or displacing fossil fuels; and can complement other variable renewable sources, especially solar, by providing complementary temporal generation profiles. Moreover, simply by providing another low carbon energy investment option, it reduces the costs of meeting climate targets, as it will be lower cost than other options in at least some locations [6]. But, realizing the benefits from offshore wind will depend heavily on continued cost reductions. These in turn depend on developing a pipeline of projects that actually reach the construction and operation stages, which will depend on streamlined and low-risk regulations and permitting and public acceptance [7]. Too often siting and permitting decisions focus exclusively on local impacts, such as those described in [8]. This work sets out to estimate the value provided by offshore wind in fighting climate change. This value provides a counterbalance to the focus on local impacts, and an impetus to reduce regulatory and other barriers.

While several states in the US have set targets for offshore wind development[3], the US hosts just 5 turbines despite having strong offshore wind resources in relatively shallow water close to load centers. This is

---

[3] AWEA 2018 US Offshore Wind Industry Status Update https://awea.org/Awea/media/About-AWEA/U-S-Offshore-Wind-Fact-Sheet-September-2018_2.pdf (Accessed: 29 December 2018).

due in part to difficulties in permitting this emerging technology [1, 9]. Complex approval processes pose a risk to offshore wind projects and present a key area where government agencies can act to reduce business risk [9]. The US government's recent, unexpected delay in permitting the first large scale offshore wind farm is a case in point. In order to balance the climate impacts against all other impacts, we develop a methodology for estimating the climate value of emerging technologies and apply it to offshore wind energy.

A number of studies have addressed the question of the climate value of energy technologies, taking one of two approaches. One set of papers estimates the emissions avoided through the use of renewable energy technologies [10]. These papers take the climate policy as given, typically a Business-as-Usual (BAU) regime. A set of papers [11–14] estimate the value of emissions displaced by technologies including land-based wind, solar, and demand management. Buonocore *et al* [15] considers the emissions that could have been displaced by proposed offshore wind farms in the US. These studies have been primarily backward-looking, considering renewable energy in the context of past or current electricity grids and existing climate policies (or lack thereof). In particular, since these papers focus only on emissions avoided, they would find no value under a policy that caps carbon emissions [16].

Another set of studies looks forward, using integrated assessment models (IAMs) to analyze the impact of specific technologies on the feasibility and cost of climate policies. In contrast to the backward looking studies, these model-based studies focus only on policies that limit emissions through caps on atmospheric CO_2 concentration. The most important studies use multiple models, focusing on how the availability of technologies impacts costs [6, 17, 18]; the implications for meeting long-term climate goals [19, 20]; or the deployment of renewable energy [21–23]. A subset of the models in these studies explicitly consider offshore wind, but specific results are rarely reported. When mentioned, the studies find it to have little impact, as they have not accounted for recent significant decreases in costs. If the offshore wind industry continues to exceed cost reduction and deployment projections, similar to solar PV, its potential to mitigate climate change may be underestimated [24].

Thus, the current literature considers either the value of avoided emissions under a BAU policy, or the value of reducing the cost of abatement, under a cap, but does not bring these together under a holistic framework that can estimate the climate value of new low carbon technologies under a range of future climate policies. We use offshore wind as a case study for this new method, but it could be applied to any new low carbon technology facing barriers to implementation.

We address this key gap in the literature, by presenting a forward-looking method to estimate the total climate value of a technology in the face of climate change, including both the value from displacing emissions and the value of reducing costs, using up-to-date costs and projections. We investigate offshore wind energy, an important emerging technology that has been largely overlooked in IAMs. In order to complete this, we developed an up-to-date set of regional supply curves for offshore wind energy; another contribution of this paper. We apply this method to investigate how the interactions between technologies—both renewable and conventional—impact the climate value of offshore wind energy under different types of climate policies to better understand the role that offshore wind can play in the energy system. This method is extremely flexible and can be applied using data from multiple IAMs, under a range of assumptions about damage functions and to any new low carbon technology to determine its climate value.

2. Methods

We develop a method to estimate the climate value of a technology under a range of policy types. We define the climate value of a low carbon technology in terms of the total cost of climate change: the sum of the cost of abatement and the cost of climate damages. Abatement is the fraction of emissions reduced below a BAU level. The present values of the cost of abatement and the cost of damages are calculated from emissions and temperature estimates, respectively. The climate value of a low-carbon technology is defined as the difference in the present value of the total cost of climate change between a case with the technology and a case without the technology, holding other parameters constant. In this way, given a climate policy and technology cost trajectory, the method accounts for what would have happened anyway, in the absence of the new technology, and only credits it with any *additional* reductions in emissions and costs. To have a positive climate value, a new low carbon technology must either reduce emissions by displacing fossil fuels or reduce costs by displacing more expensive technologies (including more expensive low carbon technologies). See section S1 in the supplementary material (SM) available online at stacks.iop.org/ERL/15/054003/mmedia for details about the model for climate value.

We use a global IAM, the Global Climate Assessment Model (GCAM) and a simple damage function, to calculate the climate value as the difference between the total cost of climate change in cases with and without offshore wind energy. The damage function converts global mean temperature change into losses in global world product (GWP), using a simple power function [25, 26]. We also evaluate the effect of a tipping point, by modeling an instantaneous and additional loss of GWP, which is not recovered even if temperature declines below the threshold after it has been reached [27–30]. The emissions data for each

Table 1. Costs of low carbon technologies in GCAM from [35] with rows added for offshore wind energy.

	Capital cost ($/kW)		Fixed O&M cost ($/kW/yr)		Variable O&M cost ($/MWh)
Technology	w/o Storage	w/Storage	w/o Storage	w/Storage	—
Onshore wind	2000	5800	50	60	0
Offshore wind (HC)	5600	10000	150	170	0
Offshore wind (LC)	3900	8300	140	150	0
Solar PV	2800	6600	40	48	0
Solar CSP	4800	8000	55	65	0
Nuclear	5500	—	95	—	2

time period resulting from GCAM are used to construct marginal abatement cost curves; the area under those curves approximates the total cost of abatement [31, 32]. Carbon taxes begin in 2020 and the model solves in five year increments to 2100. See S2 in the SM for detailed information on the methods.

We use GCAM v4.3 [33, 34] with the USA extension, described in S2 of the SM. This model does not include offshore wind, so we added this technology as described below. Table 1 shows the base costs of onshore wind, solar, and nuclear in GCAM for the year 2015 along with our high (HC) and low cost (LC) estimates for offshore wind.

We model offshore wind based on GCAM's existing structure for onshore wind [36]. Onshore wind has a base cost for the technology with and without battery storage (see table 1) and a supply curve representing the increasing costs of additional development.

We developed offshore wind energy supply curves for each of GCAM's global regions plus coastal and Great Lakes states in the US (with the exceptions of Central Asia, FL, AL, and MS)[4]. The supply curves account for cost variations related to pursuing additional projects that may be further from the grid, in areas with lower quality wind resources, and in deeper water.

Using the global areas from [37] and the US areas from [38], we estimate the annual energy production of each area from its average wind speed assuming a Weibull distribution of annual wind speeds [see 37, 39, 47 for discussion] and a capacity density of 5 MW km^{-2} [4, 37–39]. We use the water depth and distance from shore to determine the appropriate capital cost and operation and maintenance (O&M) cost for each area [41, 42]. We combine these in each region to calculate the levelized cost of energy (LCOE). More detail is available in section S3 of the SM.

We repeat these calculations to arrive at four offshore wind technology cost cases, defined by two dimensions: (1) the base cost in 2015 is either high or low and (2) the rate of technological change is either the same as onshore wind or higher such that costs decline steeply until 2030, based on estimates from the literature [3, 4] (see figure 1 and section S3 of the SM). The cases where the base costs begin high or low are abbreviated HC and LC, respectively, and we append AT (advanced technology) for cases where the costs decline rapidly.

For each region, we sort the LCOE from lowest to highest to form a supply curve (see panel (c) of figure S1). The estimated LCOE values for 2015 range from \$0.12–0.18/kWh, in line with LCOE estimates from [4]. Once the energy and cost of each area is calculated and stacked to form a rough supply curve, then a smooth curve is fitted to the data following the equation used in GCAM for onshore wind [34] (more detail in S2 of the SM).

In GCAM, energy technologies compete in the economy using a logit cost model. The logit model provides a market share for each technology that depends on the cost, with lower cost technologies taking larger market shares; but all technologies are present in at least small amounts representing niche markets, thus preventing a 'winner-take-all' result [43]. GCAM endogenously calculates the price and demand for electricity based on exogenous factors such as population, GDP and technology costs.

The global policy cases fall into three categories: BAU, carbon caps, and carbon taxes. In BAU, there is no global climate policy and therefore no value from reducing the cost of abatement. All value in this case comes from reducing emissions and resultant damages. In carbon cap cases, the level of abatement is fixed and the climate value comes only from reductions in the total cost of abatement. We use the representative concentration pathway (RCP) scenarios for 2.6 and 4.5 W m^{-2} of forcing [44, 45] for our carbon cap cases. Carbon tax cases are the third category of policies. We use carbon taxes that are similar to the carbon prices seen in the 2.6 and 4.5 RCP cases for comparison, as well as a very high carbon tax case. Under a tax, the climate value comes from both reducing emissions and reducing costs.

The costs of climate damages and the appropriate discount rates are uncertain, contested, and important to any estimate of climate value. We explore a range of values for each to explicitly address the role that each plays. We consider low, medium and high severity damages represented by exponents of 1.5, 2, and 3, respectively in the damage function [25, 26]. Similarly, we examine discount rates of 1.5%, 3%, and 5%,

---

[4] Central Asia is mostly landlocked countries and the few offshore wind resource they have in the Caspian Sea are below an average wind speed of 7 m s^{-1}, the cut off for inclusion. Area estimates for FL (Florida), AL (Alabama), and MS (Mississippi) are not included in [38] and so are not included in this work, but future work should consider developing supply curves for these states.

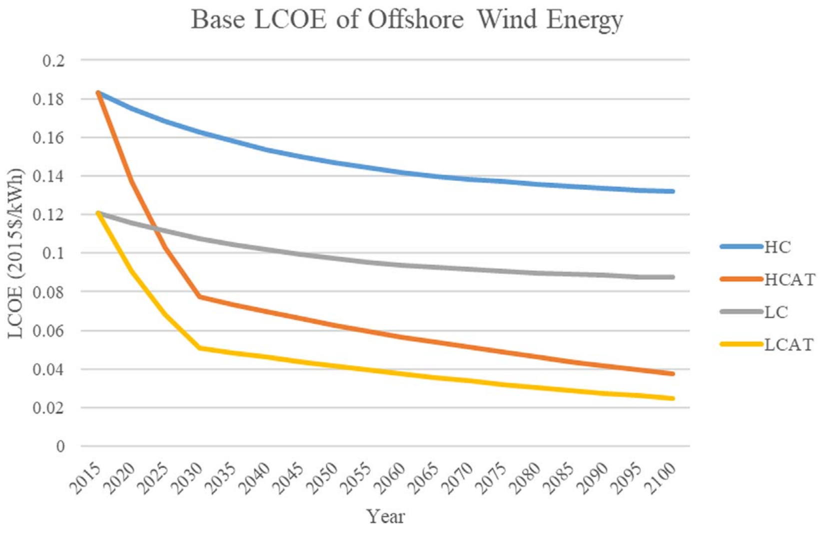

Figure 1. The levelized cost of energy in each offshore wind technology cost case over time. HC = high cost wind energy; HCAT = high cost, advanced technology; LC = low cost; LCAT = low cost advanced technology.

covering the range of values typically considered for climate change applications. These parameters are applied to the results from GCAM (more detail in section S4 of the SM).

3. Results

The global climate value of offshore wind energy is large even when discount rates are high and severity of climate damages is low. In the absence of a climate policy (i.e. BAU), and under the most unfavorable assumptions (highest cost technology, 5% discount rate, low severity damages), the net present global climate value of offshore wind energy is $24.6 billion. In the BAU case, the climate value comes from an additional reduction in emissions above what results from the currently existing low carbon technologies. This means that, even in the absence of any climate policy, even the highest cost offshore wind energy will outcompete some fossil fuels in some regions. Offshore wind energy competes for market share with all other electricity technologies based on the logit model used in GCAM (see section 2 and S2); however, any non-fossil energy displaced would not add to the climate value in this case. On a regional level, the climate value of offshore wind is driven by the use of offshore wind in place of fossil fuels, especially coal, in places like the USA and Australia where baseline coal use is high and there are excellent offshore wind resources. In contrast, the EU has considerable offshore wind potential, but uses less coal in the baseline, while India has high coal use, but little offshore wind potential (more detail in section S7 of the SM).

The climate value represents the benefit from allowing offshore wind to compete on a more equal footing with other technologies, thus it should be compared with the costs of removing barriers, such as the cost of establishing and streamlining regulatory processes and adopting stakeholder engagement processes. Under central assumptions (medium severity damages and a 3% discount rate), the climate value of offshore wind energy ranges between $246 billion and $2.5 trillion, depending on the cost of offshore wind technology. Under our most favorable assumptions (lowest cost technology, high severity damages, 1.5% discount rate), this value is $29 trillion. This implies there is a significant global value to developing streamlined processes for siting and permitting offshore wind energy, so that developers are able to build these projects where they make sense. As the cost of offshore wind energy goes down—with experience or with research and development—the total climate value of the technology increases.

To put these values in perspective with the backward-looking literature, we calculate a levelized climate value of offshore wind energy. Similar to the widely used LCOE, we divide the total climate value by the present value of all energy generated by offshore wind (more detail in section S6 of the SM). In the absence of climate policy, we estimate levelized climate values between 0.6 and 10 cents per kWh under a 3% discount rate; and between 1.4 and 2.0 under the assumption of medium severity damages. Previous literature used the social cost of carbon to estimate the value of reduced emissions. Our full range is in line with previous US-based, backward-looking estimates, which range from 0.5 to 10.2 cents per kWh [11–13, 15]; our smaller range is consistent with central estimates in these papers.

If there are tipping points in the climate system, then in cases where the addition of offshore wind avoids or delays triggering the tipping point, the climate value from reduced damages will be much larger. Under central assumptions and a $60 carbon tax, reaching 2 °C of warming is delayed in the case of

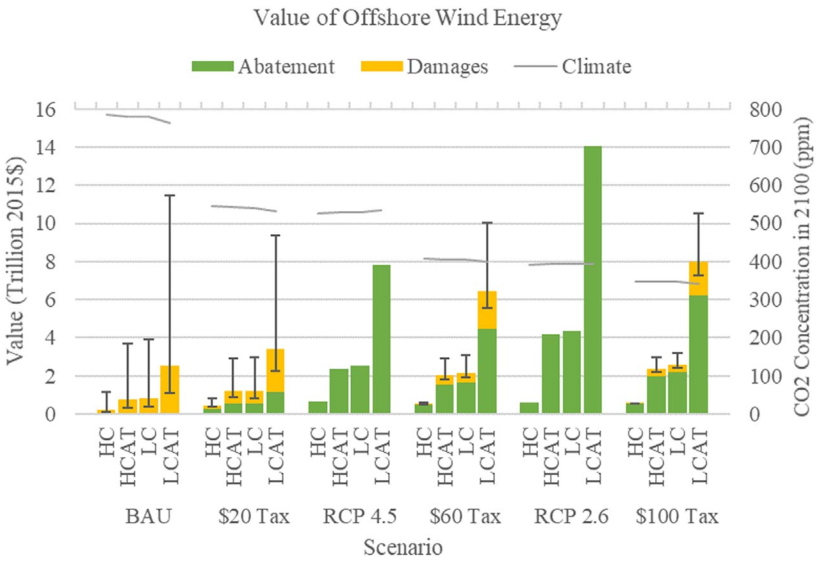

Figure 2. The global climate value of offshore wind energy between 2017 and 2100. The green portion of the bars show the value from reducing the cost of abatement. The yellow portion shows the value from reducing the cost of damages under central assumptions. The whiskers show the range of total value under low and high damage severity assumptions. Grey lines show the CO_2 concentration in 2100 (right axis). HC = high cost wind energy; HCAT = high cost, advanced technology; LC = low cost; LCAT = low cost advanced technology. See SM for detailed assumptions.

HCAT and LC and avoided altogether in the case of LCAT, leading to increases in the value of reduced damages of 1134%, 1083% and 787%, respectively (more detail in section S8 of the SM).

If other low carbon technologies are less expensive, then the climate value of offshore wind decreases. Under central assumptions, the climate value of offshore wind energy is reduced by 30%–50% if the costs of either wind and solar or the cost of nuclear are cut in half. If the costs of all three technologies are cut in half, then the climate value of offshore wind decreases by 50%–85%. The reductions in value are highest in the case of the highest cost offshore wind technology. Under central assumptions in BAU with the highest cost technology, the climate value of offshore wind energy is still $14 billion even if onshore wind, solar and nuclear are all half the cost used in GCAM. More details and sensitivity analysis provided in sections S9 and S10 in the SM.

A key benefit to this method is that we can estimate the climate value of offshore wind energy under different policy types and stringencies. Figure 2 shows these values, distinguishing between value from abatement cost reduction and value from reducing damages, under six policies, four assumptions about technology cost, three assumptions on damage severity, and a central discount rate of 3%. In the absence of climate policy, the climate value of offshore wind energy comes solely from reductions in emissions and their consequent climate damages. In contrast, under a carbon cap the climate value comes solely through reductions in the cost of abatement, as total emissions are fixed under the cap. In this case, offshore wind energy provides additional abatement opportunities at a lower price, lowering the total cost of the policy. Finally, under a carbon tax, the climate value includes both aspects, affecting both emissions and costs. As the tax increases, the value from reduced damages goes down (resulting from the convexity of the damage function), while the value from reduced abatement costs goes up. (See section S11 of the SM for the conditions under which this finding will generally hold).

The relationship between policy stringency and climate value varies under different policy types. The climate value of offshore wind always increases in the stringency of a cap. However, it is non-monotonic in the size of a carbon tax, as can be seen under the high damage severity case in figure 2. Comparing the climate value of the lowest cost technology (LCAT in the figure) and the highest damage severity (the top whisker in the figure) across BAU and the two tax cases we see that the value is lowest when the tax is $20. Under BAU, offshore wind adds significant value by displacing conventional generation and reducing severe damages. Under a $60 tax, offshore wind adds significant value by displacing the high-cost low carbon technologies employed under the higher tax. In fact, as we show in section S11 of the SM, there are general conditions under which the climate value of a technology is convex in a carbon tax, first decreasing as the technology plays an important role in decreasing damages, then increasing as the tax gets large and the technology plays an important role in decreasing costs.

Whether offshore wind has more value under a tax or a cap depends on assumptions about damage severity. The climate value under a cap does not depend on damages (since emissions are fixed with or without offshore wind), whereas under a tax the climate value increases in the severity of damages. The climate value will be approximately the same under an equivalent

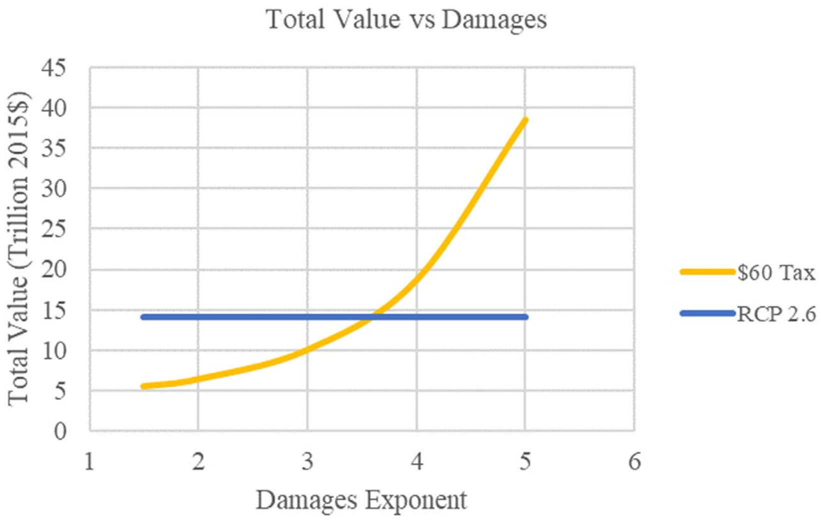

Figure 3. The global climate value of offshore wind energy as a function of damage severity under two policies, the lowest cost technology case, and a 3% discount rate.

tax and cap when the level of stringency of the policies is optimal for the given damages (see section S11.4 in the SM for more).

For example, RCP 4.5 is very close to the $20 tax, and RCP 2.6 is close to the $60 tax in terms of carbon prices and emission pathways. Yet, the climate values shown in figure 2 are different. Figure 3 compares the climate value of offshore wind energy under the 2.6 RCP and a $60 tax, as the damage severity varies. When the exponent of the damage function is 3.5, the climate value in the two cases is the same. Under the most commonly used exponent, 2, the value is higher under the cap than the tax, implying that the cap is too stringent for this level of damages given the cost estimates from GCAM. Under high levels of severity, the value under a tax becomes very high. The climate value of offshore wind is convex in the damage exponent under a tax policy and thus the expected climate value of offshore wind increases in uncertainty around climate severity for a given tax.

Taken together, these results imply that technology plays a different role under the different policies. Under a tax, technology is a hedge against uncertainty and error, providing extra value whether a tax is too high or too low for the actual damage severity. Under a cap, on the other hand, technology can provide a safety valve if the cap is too stringent, but does not provide hedging value against a cap that is too weak.

With our method, we can also examine the climate value of technological change under different future policies. The climate value of technological change is the difference in climate value between the lowest versus the highest cost technology assumptions. Figure 4 illustrates this in the BAU case, showing the climate value under the different cost assumptions. The value of technological change provides the maximum amount of climate value available through investments in R&D aimed at reducing the cost of the technology. In the BAU case this value ranges from $300 billion to $28.7 trillion depending on the severity of damages and the discount rate. Across all the other policies, the value ranges between $500 billion for a $20 tax and unfavorable assumptions to $33 trillion for RCP 2.6 and favorable assumptions. Under the most unfavorable assumptions (low severity damages and high discount rate) and regardless of the policy, the value of technological change is still more than eight times 2018 levels of R&D investment in *all* wind energy technology on an annualized basis [46]. This indicates that the world is underinvesting in these technologies.

4. Discussion

Reducing barriers to the diffusion of offshore wind energy has significant climate value. Current processes for permitting offshore wind farms in much of the world are slow and painstaking, and often put a high premium on local impacts, incorporating climate considerations in only a superficial way. It is important to include the climate value in any discussion of permitting and regulating offshore wind energy: a narrow focus on local negative impacts will result in overly restrictive permitting.

In this paper, we define a framework to estimate prospective climate value under a range of policy types. The previous literature has focused on *either* the value from reduced emissions and damages under BAU *or* on reductions in the cost of abatement under a cap. The former literature has acknowledged the difficulties of calculating climate value under a cap; and none of the existing methods can be used to calculate a climate value under a carbon tax. The conceptual breakthrough in this paper allows us to illustrate that

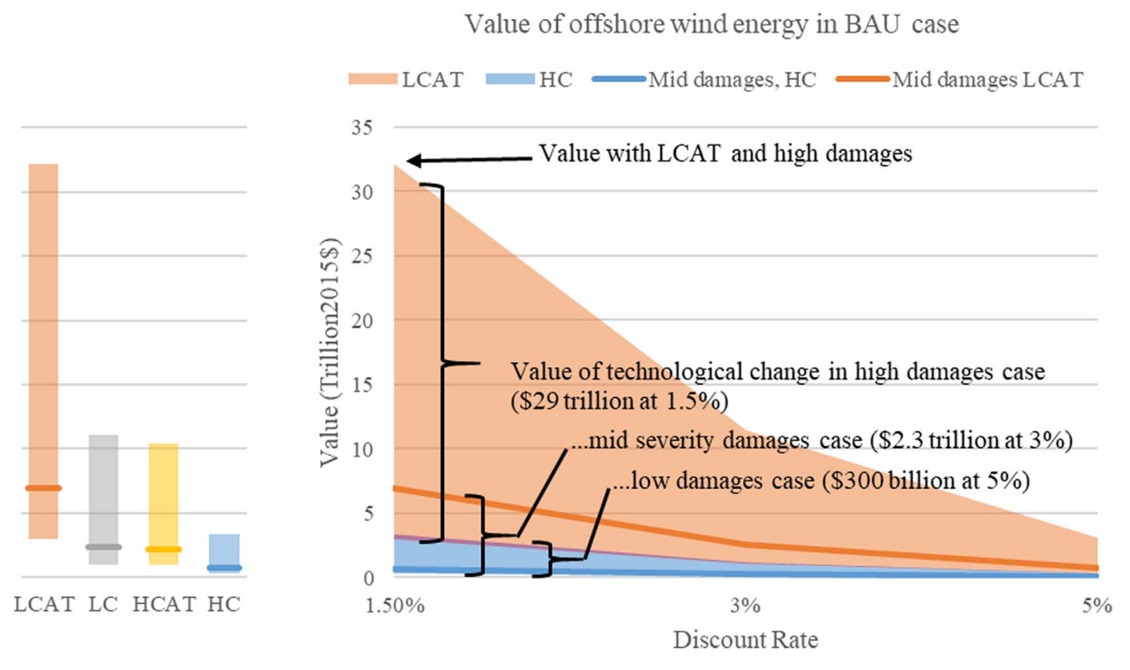

Figure 4. Climate value of offshore wind energy under different assumptions about the discount rate and severity of damages. The brackets point to the range from the highest to the lowest cost technology cases. The bottom and top of the orange shading shows the value under low and high severity damages for the lowest cost technology. The solid orange line show the value under mid severity damages. The blue shading and line show the same things, but for the highest cost technology case. The bars to the left show the range of values for each of the four technology cost cases with a 1.5% discount rate.

the climate value of offshore wind is large even under carbon cap policies, where it does not lead to lower emissions; and larger than would be identified under a carbon tax if only emissions reductions are considered. We show that the climate value is significant under a range of policies seen around the world, including no climate policy (such as at the federal level in the US), lightly-binding carbon caps (such as in EU), or significant carbon taxes (such as $100/ton seen in Sweden)[5,6]. Even under the highest cost assumptions for offshore wind and the lowest damage severity, the climate value for offshore wind is estimated to be $100, $120, and $450 billion, respectively, under these three scenarios. Regardless of the specific policy (or lack there-of), it is worth hundreds of billions of dollars to reduce the barriers to offshore wind energy. Even if other low carbon technologies (onshore wind, solar, and nuclear) turn out to be much less expensive than projected, the climate value of offshore wind remains substantial.

For a specific example of the costs of barriers, consider the Cape Wind project in Massachusetts. This received its first approval in March 2005; but after a long, drawn-out process involving scores of agencies and allowing for litigation opportunities from a focused opposition, it was finally abandoned in 2018. An ideal approval process would have identified quickly whether this was an appropriate location for a windfarm, and allowed for construction to start in this or another more appropriate location in a timely manner. The climate benefits lost from the delay between 2005 and 2020 (when the first large scale offshore wind farm in the US hopes to begin construction) are estimated to be between $140 million and $2.2 billion, using an estimate of 1500 GWh per year [47] and our levelized value under a BAU policy. Regulatory risk can lead to too little diffusion of promising technologies, exacerbating climate change along with other costs of delaying innovation.

This method highlights the different role that new technologies can play under different policy types. We see that under a tax, an emerging technology provides most value when the tax is too low, or much too high. This is likely to happen if the damages are not known for certain, or the political will is not there for setting the correct tax. In other words, in the real world. Under a cap, an emerging technology can help if the cap is too stringent, by reducing high costs, but it plays little role if the cap is too weak.

Moreover, the implied climate value of technological change in offshore wind energy is enormous even in the most unfavorable case, dwarfing world-wide R&D investments in all forms of wind energy. This provides an impetus for governments to investigate how best to encourage technical change in offshore wind; as it appears that current levels of investment do not properly account for the full climate benefits that can be achieved. Investing in technological change also hedges against errors and uncertainty in climate policies.

---

[5] European Commission EU Emissions Trading System (EU ETS) https://ec.europa.eu/clima/policies/ets_en.

[6] Government Offices of Sweden Sweden's carbon tax https://government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/.

Our estimates consider a range of parameter values, but use a specific IAM, GCAM [33, 34]. The trends in the climate value with a tax would hold with any model; but the values themselves will vary by model. GCAM has quite restrictive assumptions about grid integration and technology competition, thus it is possible that our estimates are low compared to what would be found with other models. On the other hand, the GCAM model's use of a logit function for technology cost competition implies that some amount of every technology is used, even when costs are high; this might lead to an over-estimate of the climate value of offshore wind in high-cost scenarios. We use a very simple damage function, but any damage function could be used in its place.

Addressing climate change is a complicated and multifaceted challenge. The world has low carbon technology options, but there are barriers to implementing new technologies. Those barriers have a cost. It is worthwhile putting resources into lowering the barriers to facilitate timely action under any policy future.

Acknowledgments

This work was partially supported by the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864). Thanks to the Joint Global Change Research Institute for access to their GCAM-USA model.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Files used to add offshore wind energy to GCAM are openly available from https://github.com/zcranmer/Offshore-wind-for-GCAM.

ORCID iDs

Alexana Cranmer https://orcid.org/0000-0002-5354-5931

References

[1] US DOE 2015 Wind Vision: A New Era for Wind Power in the United States *Report* (Washington, DC: USDOE) (https://energy.gov/sites/prod/files/WindVision_Report_final.pdf) (Accessed: 18 February 2019)

[2] Stehly T, Beiter P, Heimiller D and Scott G 2018 2017 Cost of Wind Energy Review *Report* (Golden, CO: National Renewable Energy Laboratory) (https://nrel.gov/docs/fy18osti/72167.pdf) (Accessed: 4 January 2019)

[3] Wiser R, Jenni K, Seel J, Baker E, Hand M, Lantz E and Smith A 2016 Expert elicitation survey on future wind energy costs *Nat. Energy* **1** 16135

[4] Beiter P *et al* 2016 A spatial-economic cost-reduction pathway analysis for US offshore wind energy development from 2015–2030 *Report* (Boulder, CO: NREL) (http://nrel.gov/docs/fy16osti/66579.pdf) (Accessed: 7 October 2016)

[5] Veers P *et al* 2019 Grand challenges in the science of wind energy *Science* **366** p.eaau2027

[6] Tavoni M, De Cian E, Luderer G, Steckel J C and Waisman H 2012 The value of technology and of its evolution towards a low carbon economy *Clim. Change* **114** 39–57

[7] Firestone J 2019 Wind energy: a human challenge *Science* **366** 1206

[8] Katzner T E *et al* 2019 Wind energy: an ecological challenge *Science* **366** 1206–7

[9] Gatzert N and Kosub T 2016 Risks and risk management of renewable energy projects: the case of onshore and offshore wind parks *Renew. Sustain. Energy Rev.* **60** 982–98

[10] Wiser R, Bolinger M, Heath G, Keyser D, Lantz E, Macknick J, Mai T and Millstein D 2016 Long-term implications of sustained wind power growth in the United States: potential benefits and secondary impacts *Appl. Energy* **179** 146–58

[11] Siler-Evans K, Azevedo I L, Morgan M G and Apt J 2013 Regional variations in the health, environmental, and climate benefits of wind and solar generation *Proc. Natl Acad. Sci. USA* **110** 11768–73

[12] Millstein D, Wiser R, Bolinger M and Barbose G 2017 The climate and air-quality benefits of wind and solar power in the United States *Nat. Energy* **2** 17134

[13] Buonocore J, Luckow P, Norris G, Spengler J, Biewald B, Fisher J and Levy J 2015 Health and climate benefits of different energy-efficiency and renewable energy choices *Nat. Clim. Change* **6** 100–5

[14] Ravikumar D, Wender B, Seager T P, Fraser M P and Tao M 2017 A climate rationale for research and development on photovoltaics manufacture *Appl. Energy* **189** 245–56

[15] Buonocore J, Luckow P, Fisher J, Kempton W and Levy J 2016 Health and climate benefits of offshore wind facilities in the Mid-Atlantic United States *Environ. Res. Lett.* **11** 074019

[16] Wiser R, Mai T, Millstein D, Barbose G, Bird L, Heeter J, Keyser D, Krishnan V and Macknick J 2017 Assessing the costs and benefits of US renewable portfolio standards *Environ. Res. Lett.* **12** 094023

[17] Kriegler E *et al* 2014 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies *Clim. Change* **123** 353–67

[18] Luderer G, Krey V, Calvin K, Merrick J, Mima S, Pietzcher R, Van Vliet J and Wada K 2014 The role of renewable energy in climate stabilization: results from the EMF27 scenarios *Clim. Change* **123** 427–41

[19] Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, Riahi K and Van Vuuren D P 2015 The impact of near-term climate policy choices on technology and emission transition pathways *Technol. Forecast. Soc. Change* **90** 73–88

[20] Luderer G, Pietzcker R C, Carrara S, de Boer H S, Fujimori S, Johnson N, Mima S and Arent D 2017 Assessment of wind and solar power in global low-carbon energy scenarios: an introduction *Energy Econ.* **64** 542–51

[21] Creason J R, Bistline J E, Hodson E L, Murray B C and Rossmann C G 2018 Effects of technology assumptions on US power sector capacity, generation and emissions projects: results from the EMF 32 model intercomparison project *Energy Econ.* **73** 290–306

[22] Mai T, Bistline J, Sun Y, Cole W, Marcy C, Namovicz C and Young D 2018 The role of input assumptions and model structures in projections of variable renewable energy: a multi-model perspective of the US electricity system *Energy Econ.* **76** 313–24

[23] Victor N, Nichols C and Zelek C 2018 The US power sector decarbonization: investigating technology options with MARKAL nine-region model *Energy Econ.* **73** 410–25

[24] Creutzig F, Agoston P, Goldschmidt J C, Luderer G, Nemet G and Pietzcker R C 2017 The underestimated potential of solar energy to mitigate climate change *Nat. Energy* **2** 17140

[25] Nordhaus W and Sztorc P 2013 *DICE 2013R: Introduction and User's Manual* 2 edn (New Haven, CT: Yale University Press)

[26] Hope C W 2011 The social cost of CO_2 from the PAGE09 model *Economics Discussion Paper* No. 2011–39 (http://economics-ejournal.org/economics/discussionpapers/2011–39/file) (Accessed: 1 May 2016)

[27] Keller K, Bolker B M and Bradford D F 2004 Uncertain climate thresholds and optimal economic growth *J. Environ. Econ. Manage.* **48** 723–41

[28] Lemoine D and Traeger C 2014 Watch your step: optimal policy in a tipping climate *Am. Econ. J.: Econ. Policy* **6** 137–66

[29] Lemoine D and Traeger C P 2016 Economics of tipping the climate dominoes *Nat. Clim. Change* **6** 514–20

[30] Lontzek T S, Cai Y and Judd K L 2012 Tipping points in a dynamic stochastic IAM *RDCEP Working Paper No 12-03* (https://doi.org/10.2139/ssrn.1992660)

[31] Baker E, Clarke L and Shittu E 2008 Technical change and the marginal cost of abatement *Energy Econ.* **30** 2799–816

[32] Barron R, Djimadoumbaye N and Baker E 2014 How grid integration costs impact the optimal R&D portfolio into electricity supply technologies in the face of climate change *Sustain. Energy Technol. Assess.* **7** 22–9

[33] Fawcett A A *et al* 2015 Can Paris pledges avert severe climate change? *Science* **350** 1168–9

[34] Pacific Northwest National Laboratory (PNNL) 2016 GCAM v4.3 Documentation: Global Change Assessment Model (GCAM) (College Park, MD: JGCRI) (http://jgcri.github.io/gcam-doc/) (Accessed: 1 May 2016)

[35] Muratori M, Ledna C, McJeon H, Kyle P, Patel P, Kim S H, Wise M, Kheshgi H S, Clarke L E and Edmonds J 2017 Cost of power or power of cost: a US modeling perspective *Renew. Sustain. Energy Rev.* **77** 861–74

[36] Zhou Y, Luckow P, Smith S J and Clarke L 2012 Evaluation of global onshore wind energy potential and generation costs *Environ. Sci. Technol.* **46** 7857–64

[37] Eurek K, Sullivan P, Gleason M, Hettinger D, Heimiller D and Lopez A 2017 An improved global wind resource estimate for integrated assessment models *Energy Econ.* **64** 552–67

[38] Schwartz M N, Heimiller D, Haymes S and Musial W 2010 Assessment of offshore wind energy resources for the United States *Report* (Golden: NREL) (http://nrel.gov/docs/fy10osti/45889.pdf) (Accessed: 15 January 2016)

[39] Musial W, Heimiller D, Beiter P, Scott G and Draxl C 2016 2016 Offshore wind energy resource assessment for the United States *Report* (Goldne, CO: NREL) (http://nrel.gov/docs/fy16osti/66599.pdf) (Accessed: 12 October 2016)

[40] Manwell J F, McGowan J G and Rogers A L 2009 *Wind Energy Explained: Theory, Design and Application* 2nd Edn. (West Sussex: Wiley)

[41] Myhr A, Bjerkseter C, Ågotnes A and Nygaard T A 2014 Levelised cost of energy for offshore floating wind turbines in a life cycle perspective *Renew. Energy* **66** 714–28

[42] Bjerkseter C and Ågotnes A 2013 Levelised costs of energy for offshore floating wind turbine concepts *MSc Thesis* Norwegian University of Life Sciences, Ås, Norway

[43] Clarke J F and Edmonds J A 1993 Modelling energy technologies in a competitive market *Energy Econ.* **15** 123–9

[44] van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

[45] Thomson A M *et al* 2011 RCP4.5: a pathway for stabilization of radiative forcing by 2100 *Clim. Change* **109** 77–94

[46] Frankfurt School-UNEP Centre/BNEF 2018 *Global Trends in Renewable Energy Investment 2018* (Frankfurt: Frankfurt School UNEP Centre) (http://greengrowthknowledge.org/resource/global-trends-renewable-energy-investment-report-2018) (Accessed: 9 November 2018)

[47] Bureau of Ocean Energy Management (BOEM) 2018 Cape Wind (https://boem.gov/Massachusetts-Cape-Wind/) (Accessed: 13 November 2018)