Estimating the Value of Offshore Wind Along the United States' Eastern Coast

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Abstract

Offshore wind power deployment has been concentrated in Europe, and remains limited in other areas of the world. Among the many challenges to deployment is the need to understand the value that offshore wind provides within electricity markets. This article develops a rigorous method to assess the economic value of offshore wind along the eastern coastline of the United States, seeking improved understanding of how the value of offshore wind varies both geographically and over time, and what has driven that variation. The article uses historical (2007-2016) weather data at thousands of potential offshore wind sites, combined with historical wholesale electricity market outcomes and renewable energy certificate (REC) prices at hundreds of possible transmission interconnection points. We find that the average historical market value of offshore wind from 2007-2016—considering energy, capacity, and RECs—varies significantly by project location, from \$40/MWh to more than \$110/MWh, and is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts. As energy and REC prices have fallen in recent years, so too has the market value of offshore wind. The historical value of offshore wind is found to exceed that of onshore wind, due to offshore wind sites being located more favorably in terms of constrained pricing points, and also due to a more-favorable temporal profile of electricity production. Finally, we explore multiple ways to enhance the value proposition for offshore wind, including strategies associated with interconnecting to higher-priced locations and the addition of electrical storage. Whether any of these strategies, and offshore wind more generally, is economically attractive will depend on tradeoffs between value and cost. Cost reductions that approximate those witnessed recently in Europe may be needed for offshore wind to offer a credible economic value proposition on a widespread basis in the United States.

1. Introduction

On a global basis, wind power has experienced rapid deployment in recent years, reaching 487 GW of capacity (GWEC 2017) and nearly 5% of global electricity supply (Wiser and Bolinger 2017) by the end of 2016. Most of this development has occurred on land, but offshore wind power installations have accelerated in recent years—especially in Europe and, more recently, in China (GWEC 2017).

The United States, meanwhile, hosts only a single, small (30 MW) offshore wind project. Commonly noted barriers to the offshore wind industry in the U.S. include high costs and stiff competition from other lower-cost resources (including natural gas, onshore wind, and solar photovoltaics), a complex and lengthy regulatory process for planning and siting, and a lack of pre-existing infrastructure to manage construction at low cost (DOE and DOI 2016; Musial et al. 2017; Grace et al. 2017). Despite these barriers, offshore wind remains of interest (DOE 2015; Musial et al. 2017; DOE and DOI 2016; Grace et al. 2017; Firestone et al. 2015), given that the offshore wind resource is vast (Musial et al. 2016) and that site conditions along the U.S. eastern coast are generally favorable, with relatively strong winds and shallow waters (Beiter et al. 2016). Moreover, the offshore wind resource is located near major population centers, and so does not require investment in long-distance transmission (DOE 2015). And large project sizes are possible, a luxury relative to the much smaller land-based renewable energy projects that can be developed in the populous eastern United States (DOE and DOI 2016). Finally, at least on the east coast, offshore wind competes with somewhat higher-cost alternative resources than in other parts of the country—e.g., onshore wind and solar resources are less favorable in the East than in other regions.

Notwithstanding the arguments in favor of or against aggressive offshore wind deployment in the United States, there remains an unclear understanding of the economic value that offshore wind provides within local or regional electricity markets. This lack of clarity is due, in part, to the fact that offshore projects can be developed in many different locations, and that diurnal and seasonal wind resource profiles vary by project location. Differences in location and location-specific generation profiles can affect the value of wind power in terms of which other generators wind displaces (and hence both the type and quantity of fuels and emissions that wind power reduces), wind's contribution to meeting peak demand, and the local price of electricity and renewable energy credits (RECs) that wind earns.

With these and other value components in mind, this article seeks to provide insight into the economic and environmental value that offshore wind offers along the eastern coast of the United States. Specifically, this work explores the question: What would the marginal value of offshore wind projects along the east coast of the United States have been from 2007-2016, had any such projects been operating during that time period? Using historical weather data at thousands of potential offshore wind sites, combined with historical wholesale electricity market outcomes and REC prices at hundreds of possible transmission interconnection points, we develop a rigorous method to answer this question, focusing mostly on marginal economic value but also including environmental impacts.

We consider energy, capacity and REC value, avoided air emissions, the wholesale electricity price 'merit-order' effect, and natural gas price suppression. In addition to assessing each value component, and how value has varied geographically and over time, we evaluate value differences between offshore and onshore wind, the capacity credit of offshore wind, the value of interconnecting at and selling to different locations, the incremental value of storage, and the impact of different wind turbine designs. We contrast these historical value estimates with the possible cost of current and future offshore wind projects. Finally, we conclude by discussing, at a high level, various factors that might drive each value component higher or lower in the future.

Although the historical nature of this analysis should be noted—limiting its applicability going forward—knowing how the historical value of offshore wind has varied both geographically and over time, and what has driven that variation, provides important insights to a variety of stakeholders. These include, perhaps most prominently, energy policymakers considering offshore-specific incentive programs and mandates as well as those in the energy industry exploring offshore wind. Focusing on market value may also help to inform public and private R&D efforts by highlighting the cost targets that need to be achieved if offshore wind deployment is to accelerate.

2. Background

Previous research has focused on both the cost and value of offshore wind. Historical cost trends have been mixed. An initial reduction in costs among the early fixed-bottom offshore wind projects in the 1990s was followed by *increasing* costs in the 2000s (e.g., as projects moved further from shore) and, most recently, indications of steep cost reductions in European tenders (Dismukes and Upton Jr. 2015; Voormolen, Junginger, and van Sark 2016; Musial et al. 2017; Heptonstall et al. 2012). While some question the likelihood of significant future cost reductions (Schwanitz and Wierling 2016), wind experts (Wiser et al. 2016) and recent tenders (Musial et al. 2017) alike suggest ongoing expectations for sizable cost reductions in the coming years and decades.

Given offshore wind's high costs historically, researchers and project developers have sought to convey the value of offshore wind as part of a larger electricity supply portfolio. Research has emphasized the favorable output profile and/or location of offshore wind along the eastern seaboard, sometimes in comparison to the output profile and need for transmission associated with onshore wind (Bailey and Wilson 2014; Mai et al. 2012; Wilson 2014; Dvorak et al. 2012, 2013; GE Energy 2005, 2010, 2014; NY-ISO 2010; SACE 2013; ISO-NE 2017, 2016b; Lin 2016). This body of work has found that offshore wind has greater 'market value' than onshore wind (considering energy and capacity), consistent with wind deployment experience in Germany (Ederer 2015). Others have highlighted the possible role of offshore wind in reducing wholesale electricity prices via the 'merit-order' effect and/or in suppressing natural gas prices (ISO-NE 2016a; GE Energy 2010, 2014; CRA 2012; Simão et al. 2017; ABB 2014; Tabors, Rudkevich, and Hornby 2014; Tabors et al. 2015; Pfeifenberger and Newell 2010; EnerNex 2011). Research has also assessed the climate and health benefits associated with offshore wind deployment (Buonocore et al. 2016; Chiang et al. 2016; Kempton et al. 2007; ISO-NE 2016a; Simão et al. 2017), and the local economic development impacts associated with building and servicing offshore wind installations (BVG 2017; Tegen et al. 2015).

Still other work has sought to bring these two strands together, comparing the cost and value of offshore wind (Levitt et al. 2011; Beiter et al. 2017) and estimating the role and value of offshore wind in future electricity portfolios in the U.S. (DOE 2015) and globally (Gernaat et al. 2014).

This study builds on this previous work in several respects. First, we assess the value of offshore wind along the entire eastern seaboard of the United States, enabling a comprehensive assessment of the relative value of offshore wind across many different locations and in comparison to onshore wind. Second, we assess a large number of possible value components, reflecting both economic and environmental considerations. Third, we capture the full range of spatial and temporal variation observed in both wind resource conditions and electric system characteristics. Fourth, we analyze several means of boosting the value of offshore wind, while also comparing the value of offshore wind to its current and potential future cost. Finally, by applying unique datasets over a lengthy historical period, we are able to explore how the value of offshore wind has varied both geographically and over time, and what has driven that variation.

3. Methods

3.1 Wind Energy Sites, Speeds, and Output Profiles

We used NREL's Wind Toolkit (Draxl et al. 2015) to identify potential offshore wind sites along the U.S. eastern seaboard (from Maine to northern Florida, and considering sites suitable for both fixed-bottom and floating-platform installations), screening out those sites that are insufficiently windy (< 7 m/s average at 100 m) or are in especially deep (>1000 m) or non-US waters. The Wind Toolkit is the most-extensive, publicly available grid-integration wind dataset available in the United States, providing simulated wind speeds on a 2-km x 2-km geographic scale. For our purpose, the Wind Toolkit provides estimated hourly wind speeds at each of the 6,693 sites contained in our analysis, from 2007-2013. To extend each site's hourly time series through 2016, we relied upon coarser reanalysis data from MERRA (Gelaro et al. 2017). At each site, a separate regression, between the Wind Toolkit wind speed and corresponding MERRA wind speed, was developed for each hour of the day and for four seasons, leading to 4 × 24 = 96 regression equations for each site. Our method is broadly classed as a 'measure-correlate-predict' approach, similar to that described in Carta et al. (2013), although sectioned by time and season rather than wind direction. A cross validation of seasonal and diurnal wind speed cycles demonstrated that the method reasonably approximated the more-detailed Wind Toolkit data, and led to low errors (<3% MAE) in wholesale value estimates on an annual basis.

Wind speed is then converted to wind power using a representative power curve for a 6 MW wind turbine with a 155 m rotor and a hub height of 100 m (Musial et al. 2016). Net output assumes 96% availability and includes assumptions for wake, electrical, and other losses that can vary by site and hourly wind speed. Further details on this and other aspects of the methodology can be found in Mills et al. (2018).

3.2 Value Quantification

Each offshore wind site that falls within one of the three organized Independent System Operator (ISO) markets along the coast—i.e., ISO New England (ISO-NE), the New York ISO (NYISO), or the PJM Interconnection (PJM)—is then paired with the nearest wholesale market pricing point with substantial capacity (defined as any pricing point with a substation having a voltage of more than 138 kV or associated with more than 200 MW of generation). Each of these pricing points, in turn, is mapped to a specific ISO, ISO capacity zone (to estimate capacity value), and state (to estimate REC value, as well as reductions of both emissions and natural gas prices).

Energy value is based on the wind plant's hourly net output multiplied by hourly nodal real-time energy prices at the interconnection point (i.e., locational marginal prices, or LMPs). The hourly LMP accounts for the timing of when energy is cheap or expensive and it embeds the cost of congestion, transmission-level losses and, depending on the region, the compliance cost of various emissions regulations. Capacity value is based on the wind plant's capacity credit (estimated using each ISO's rules in place at the time—see Mills et al. (2018)) multiplied by the ISO capacity zone's prices. REC value is based on monthly pricing for compliance-based RECs in each state with a renewable portfolio standard (RPS), multiplied by monthly net generation. Offshore projects are assumed to sell RECs into the RPS compliance market of the same state where the project interconnects, except that if no RPS exists in the year in question, the project is assumed to sell into the highest-priced REC market in the ISO-defined region. We conduct a 'marginal' analysis, in effect assessing the value associated with the first offshore wind plants; some of the values estimated here would be expected to decline as offshore wind penetrations increase.

Wind sites that fall outside of the three organized ISO markets (i.e., those off the coast of most of North Carolina and all of South Carolina, Georgia, and Florida) are mapped to utility balancing areas (based on state boundaries) rather than to specific wholesale market pricing points. In these instances, energy value is based on published 'system lambdas' (i.e., each balancing authority's estimate of marginal generating costs within its balancing area) rather than nodal pricing; capacity value is approximated based on capacity prices from the southernmost capacity zone in PJM and the capacity credit rules for PJM; and REC value is based on monthly RPS-based REC prices where they exist, or national voluntary REC prices in those states without an RPS (South Carolina, Georgia, Florida).

In addition to energy, capacity, and REC value (which, collectively, reflect the potential total market revenue of a merchant offshore plant, or the avoided costs for a purchaser of offshore wind), we also estimate the air emissions reductions associated with offshore wind, as well as the reduction in natural gas prices resulting from displaced gas-fired generation suppressing natural gas demand. For both purposes, we use the Environmental Protection Agency's (EPA's) AVoided Emissions and geneRation Tool (AVERT). Other research that has used AVERT for similar purposes includes Barbose et al. (2016), Millstein et al. (2017), and Chiang et al. (2016). AVERT assesses—on a statistical basis—electricity system dispatch regionally (including for the three broad regions that encompass the U.S. east coast) and, among other things, tracks both the emissions rate and natural gas consumption of generators estimated to be on the margin—and hence able to be displaced by offshore wind—in each hour. Following previous work by Barbose et al. (2016) and Wiser and Bolinger (2007) to estimate the natural gas price suppression effect, we take the volume of gas displacement estimated by AVERT and apply an inverse elasticity of supply consistent with that used by the Energy Information Administration (EIA 2017) to estimate the level of price reduction nationally. Total dollar savings nationally and regionally are then the product of the price reduction and national or regional gas demand.

Finally, we estimate reductions in wholesale electricity prices resulting from the 'merit order' effect (i.e., low marginal cost offshore wind displacing higher-cost generation from the bid stack). Specifically, following Navigant (2011), for each ISO and each year, we estimate the historical change in prices with a change in supply for each hour using statistical relationships between wholesale prices and demand and natural gas prices, and then apply those relationships when assessing the impact of offshore wind. In the non-ISO region south of PJM we use the system lambdas instead of the energy component of the LMP to develop this relationship. Following Chernick and Neme (2015) we assume that loads in the ISO regions use contracts to hedge 60% of their load and that vertically integrated utilities in the non-ISO region hedge 80% of their load.

It is important to recognize that these latter two effects—i.e., natural gas and wholesale electricity price suppression—are technically wealth transfers from gas producers and electricity generators to consumers. While some decision-makers consider these effects, others do not treat these as net societal "benefits" that create true economic value per se (Barbose et al. 2016; Felder 2011).

3.3 Factors Not Considered

Several factors that may influence the perceived or actual value of offshore wind are not assessed in this analysis. First, we do not account for any costs associated with the short-term (i.e., sub-hourly) variability and forecast error of offshore wind. These costs are generally found to be modest, at $1-7/MWh (EnerNex Corp. 2010; Wiser et al. 2011; UKERC 2017). Second, we calculate the value of offshore wind 'on the margin' assuming that the addition of offshore wind does not impact the revenues of wind. In contrast, we do account for the impact of wind on consumer costs through the wholesale price 'merit order' effect since even small effects on prices can have large impacts on overall consumer costs. Third, the wholesale price 'merit order' effect does not account for any local price suppression associated with congestion and losses, but instead focuses on region-wide effects (other research has found a magnified local effect, e.g., CRA (2012), Pfeifenberger and Newell (2010), and EnerNex (2011)). It also does not account for any potential reduction in forward capacity market prices; one study suggests that this latter omission may be meaningful, at least in the constrained region of Long Island (Tabors, Rudkevich, and Hornby 2014). Fourth, avoided air emissions are quantified in physical terms, but are not assessed in terms of health outcomes (for research that has focused on the health outcomes of offshore wind, see Buonocore et al. 2016, and Chiang et al. 2016). Instead, these emissions reductions are valued to some extent through pollution permit prices embedded in LMPs, and through RECs. Fifth, avoided transmission costs are only addressed through the congestion component of the LMP prices. Finally, the analysis does not estimate the economic value or cost of other community, economic development, and environmental effects (e.g., water use, employment, tourism, property values, fishing impacts, etc.).

4. Results

4.1 The Value of Offshore Wind

We start with a focus on those market values that directly influence the revenue earned by an offshore wind project (or the avoided costs for a purchaser of offshore wind): energy value, capacity value, and REC sales. With that focus, we find that the marginal market value of offshore wind varies significantly by project location.

In particular, Figure 1 shows that the total market value (i.e., energy, capacity, and REC value combined) of offshore wind is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts; lower for projects off of Maine; and lowest elsewhere along the coast. When averaged over the entire 2007-2016 period (left half of Figure 1), the marginal median value for sites interconnecting to ISO-NE is roughly $110/MWh, compared to $100/MWh for sites interconnecting to NYISO, $70/MWh for sites in PJM, and closer to $55/MWh for sites in the non-ISO region south of PJM. When focusing on just 2016 (right half of Figure 1), the corresponding marginal values are much lower (for reasons explained later), but the relative differences across states and regions is still similar. The median value for sites in ISO-NE is $70/MWh in 2016, and for NYISO is nearly $65/MWh. The median value of sites in PJM is $45/MWh, while it is less than $40/MWh for sites in the non-ISO region south of PJM.

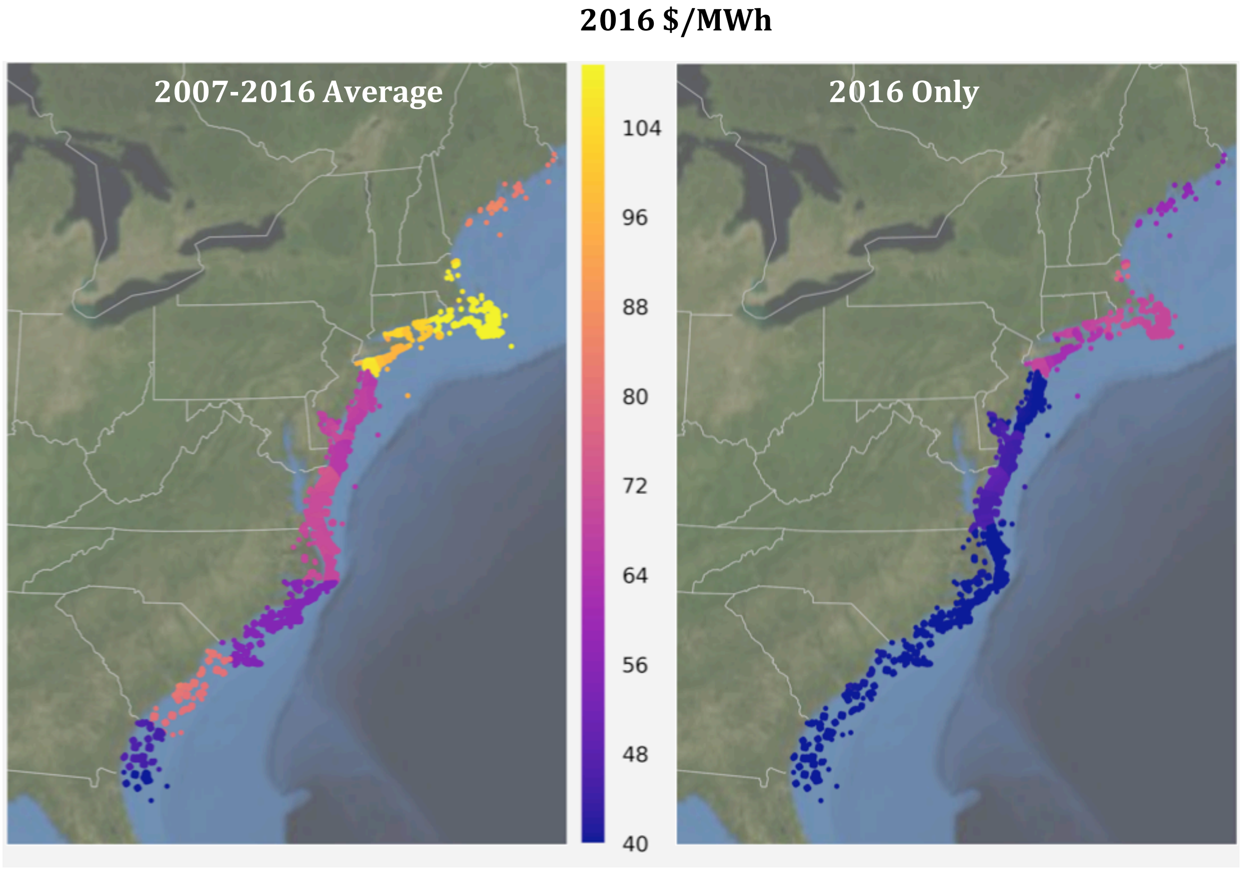

Figure 1. Total market value at each site, averaged over 2007-2016 (left) and for 2016 only (right), considering the combined value of energy, capacity, and RECs

Further investigation finds that the historical market value of offshore wind has resembled that of a 24x7 flat block of power. In other words, the locational variation in the market value has been driven primarily by differences in average energy (and REC) prices across pricing points, states and regions, rather than by differences in diurnal and seasonal wind generation profiles across project sites. This insight is revealed by controlling for locational differences in pricing, accomplished in the left pane of Figure 2 by dividing the total market value of offshore wind at each site (averaged over 2007-2016—i.e., the values from the left pane of Figure 1) by each site's average energy, capacity, and REC prices across all hours. In other words, Figure 2 compares the marginal revenue earned by each offshore wind project to the amount of revenue it would have earned if generating the same total amount of annual energy but with no temporal variation in output. The resulting 'normalized' market value (total, energy, and capacity, respectively, from left to right) of offshore wind shown in Figure 2 indicates whether offshore wind is more or less valuable than a 24x7 flat block of power; variation in this metric across sites solely reflects differences in diurnal and seasonal generation profiles.

As shown in Figure 2, the normalized total market value of offshore wind (left pane) ranges from 95%-105%, with the largest ratios found in NYISO, ISO-NE, and off the coast of North Carolina. The energy value component (middle pane) tells a similar story, and with a similarly modest range (98%-108%). In contrast, the normalized capacity value component (right pane) varies more significantly, from 50%-120% (capacity value is explored in more depth below). The rather modest ranges for both total and energy value indicate that variability in wind generation profiles across sites is not a strong determinant of marginal offshore wind market value along the East Coast; instead, the significant variation in market value seen in Figure 1 is driven much more by local energy (and REC) prices. In other words, the market value of offshore wind is roughly similar to that of a similarly located flat block of power, at least on a marginal basis for the first offshore wind plants.

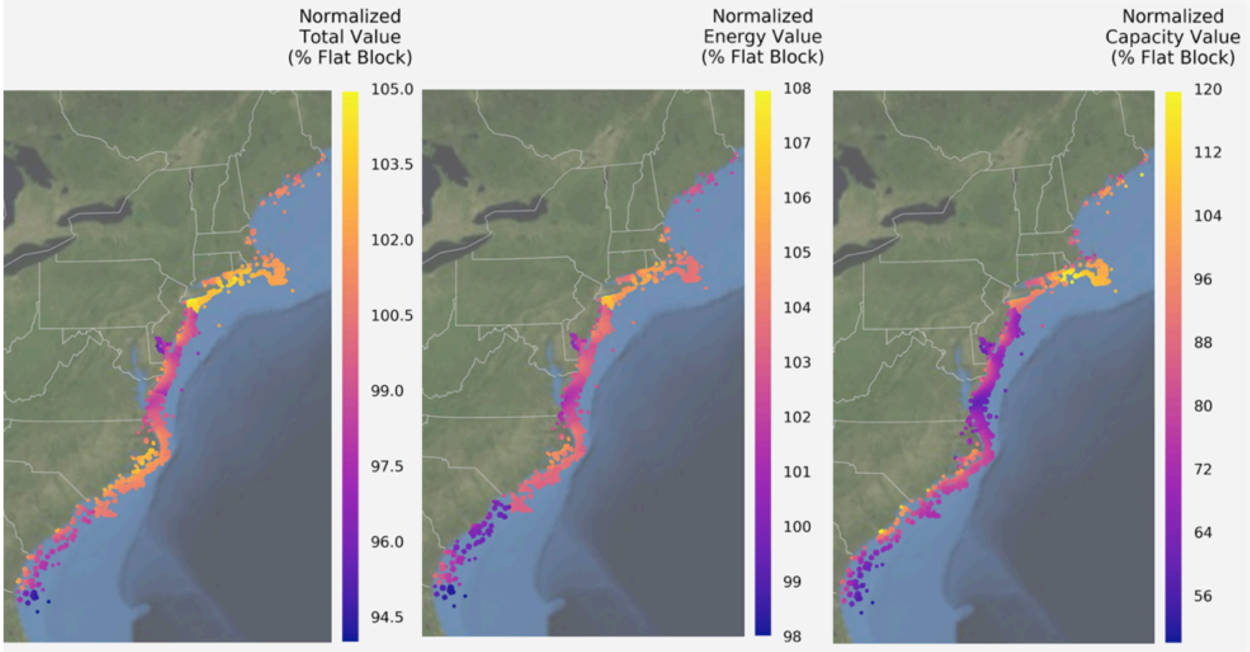

Figure 2. Normalized total market value and its energy and capacity components

To be clear, diurnal and seasonal generation profiles do distinguish among offshore sites, but mostly for capacity value, which is a small component of overall value. The relatively wide range (50%-120%) in normalized capacity value shown in the right pane of Figure 2 solely reflects differences in wind generation profiles across sites (as well as the rules by which wind plants earn capacity payments), with sites off of Rhode Island and Massachusetts having the most advantageous profiles in terms of aligning with capacity measurement periods. Similarly, winter capacity credits are highest for the areas off of Rhode Island and Massachusetts (see Figure 3). Figure 3 also shows the distribution of summer capacity credit along the entire east coast. Note that winter capacity credits are shown for NYISO and ISO-NE sites only, as PJM does not assess capacity credits in the winter (we also assume that PJM capacity market rules apply to all states south of PJM). The capacity credit of offshore wind in the NYISO and ISO-NE markets is significantly higher in winter than in summer; offshore wind in these regions benefits from having capacity credit assessed in both seasons. Despite the significant variation in capacity credit (Figure 3) and normalized capacity value (Figure 2) across sites, however, capacity value is a relatively minor component of the total market value, as shown later in Figure 4.

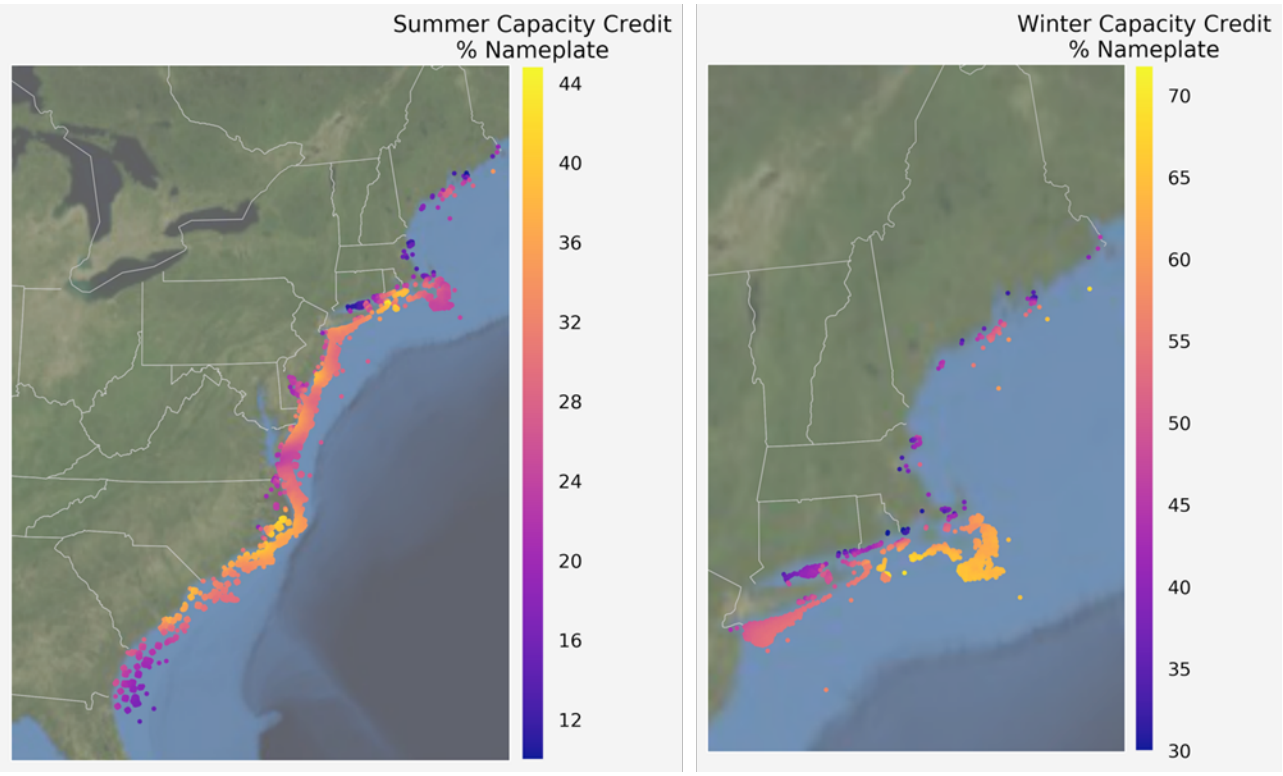

Figure 3. Capacity credit of offshore wind in summer and winter

In addition to varying geographically, the market value of offshore wind also varies significantly from year to year, driven primarily by changes to energy and REC prices. The market value of offshore wind is lowest in 2016, the most recent year evaluated. This inter-year variation was first seen in Figure 1, where the total market value of offshore wind in 2016 was significantly lower than the value averaged over 2007-2016. Figure 4 shows that this significant decline in total market value is attributable primarily to lower electricity prices in 2016, which reduced the median energy value of offshore wind to ~$30/MWh across all four regions. Figure 4 also confirms that the capacity value of offshore wind is only a small component of total value. Variability in total market value over time has been driven by both electricity and REC prices (with the former heavily influenced by natural gas prices). The total market value is highest in ISO-NE, in part due to higher REC prices, while energy and capacity value is highest for NYISO, particularly for the Long Island region.

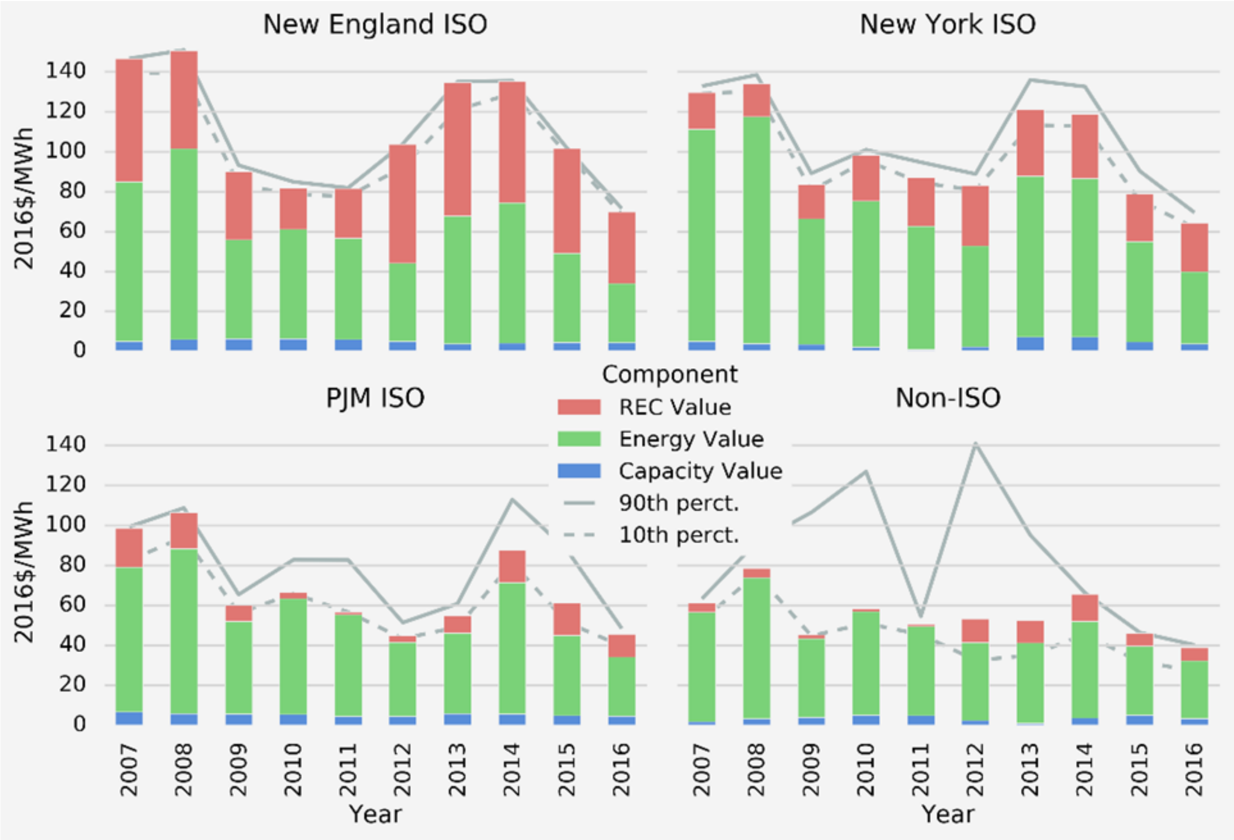

Figure 4. Median energy, capacity, and REC value by year for sites within each region. The lines show the 10th (dashed) and 90th (solid) percentile of the total market value across all sites within each region.

Confirming earlier work, the historical energy and capacity value of offshore wind in all three ISOs is found to have exceeded the value of onshore wind. Specifically, we use the actual historical, ISO-wide hourly output of onshore wind to estimate the energy and capacity value of onshore wind in each ISO, and compare those figures to the value of the median offshore wind site in each ISO. In 2016, the total energy and capacity value of offshore wind would have exceeded the value of existing onshore wind by $6/MWh (or 21%) in ISO-NE, $6/MWh (or 24%) in PJM, and by more than $20/MWh (112%) in NYISO (Figure 5). The differences in energy and capacity value between onshore and offshore wind are due both to differences in location and differences in hourly output profiles: location appears to play a somewhat larger role than output profile, in most cases. The estimated summer and winter capacity credit for offshore wind in the three ISOs is roughly double that for onshore wind.

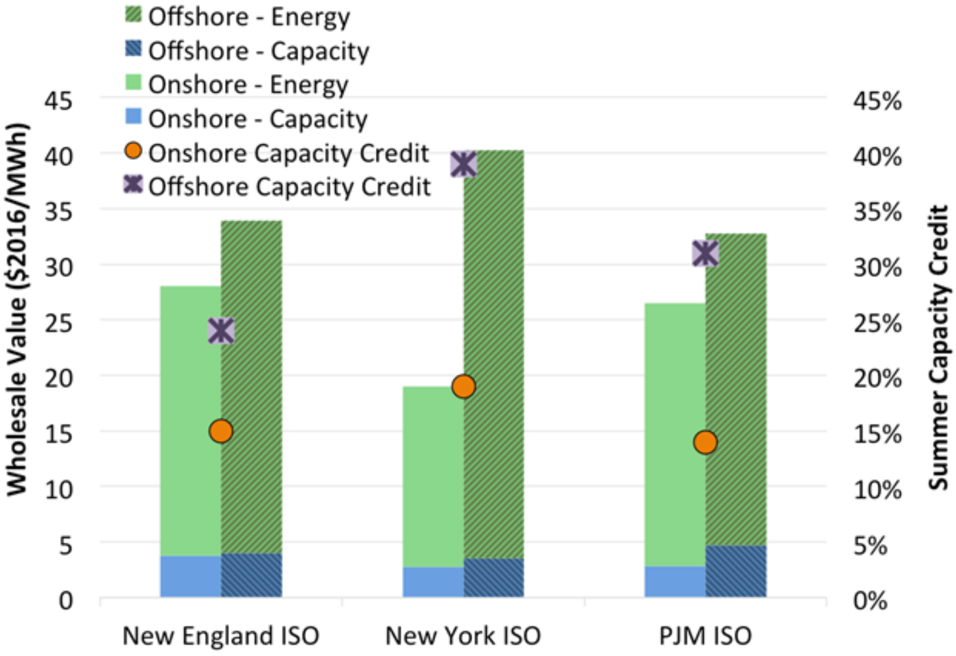

Figure 5. Comparison of 2016 energy and capacity value for offshore and onshore wind

In addition to its market value, offshore wind reduces air emissions that are harmful to human health and the environment. Figure 6 shows that avoided emissions attributable to offshore wind vary by region, based on the degree to which coal or natural gas is displaced—highest in the Mid-Atlantic, lower in the Southeast, and lowest in the Northeast—and have generally declined over time, as the emissions rate of the marginal generator has improved. The decline over time has been particularly steep for SO_2 (top left graph), as coal plants have either retired or installed pollution control equipment. Although avoided emissions is a measurable benefit of offshore wind, the economic value of avoided emissions is not necessarily fully additive to the energy, capacity, and REC value discussed earlier. This is because some of this value is already embedded in energy value, since pollution permit prices, to the extent that they affect the variable costs of marginal plants, are reflected in LMPs. Additionally, one could argue that REC value partially reflects the benefits of avoided emissions. That being said, other research efforts have found substantial value to the air quality benefits from wind power production in these regions. For example, Buonocore et al. (2016) find that offshore wind in the Mid-Atlantic would provide between $54/MWh to $120/MWh of health and climate in benefits in 2017 and Millstein et al. (2017) find central estimates of air quality benefits from existing onshore wind worth $26/MWh, $110/MWh, and $44/MWh in the Northeast, the Mid-Atlantic, and the Southeast regions, respectively, in 2015.

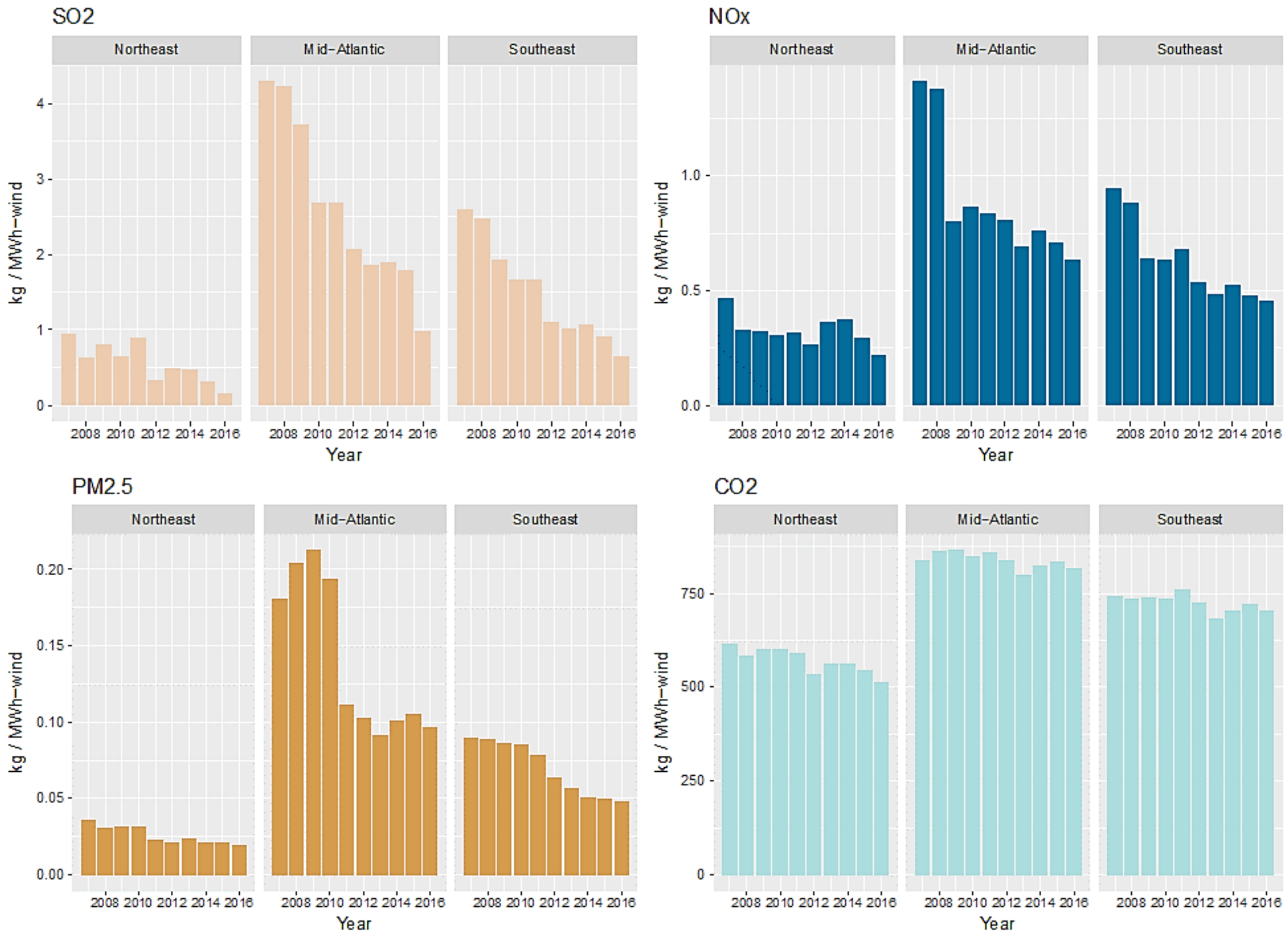

Figure 6. Avoided SO_2 (top left), NO_x (top right), $PM_{2.5}$ (bottom left), and CO_2 (bottom right) emissions rate by year for average offshore wind profile in each region

When the marginal generation unit displaced by offshore wind is a gas-fired generator, offshore wind not only avoids emissions but also reduces the consumption of natural gas. Because natural gas supply is relatively inelastic in the short term, reductions in natural gas demand can lead to price reductions, resulting in flow-through consumer benefits in the form or lower natural gas expenditures throughout the economy.[1] For example, we estimate that natural gas price savings nationwide could have an equivalent value per-MWh of offshore wind of \$30-\$80/MWh of offshore wind when averaged over 2007-2016, depending on in which region the offshore wind is located. Local regional price savings within the region in which the offshore wind plant interconnects are much lower, but still significant, at less than \$6/MWh of offshore wind (Figure 7). Similarly, low-marginal-cost offshore wind also reduces wholesale electricity prices by displacing the highest-cost marginal generating units from the bid stack. When translated to an equivalent consumer benefit per-MWh of offshore wind, we estimate this ‘merit

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[1] The same effect could occur with coal and other fuels displaced by offshore wind generation, but likely at a much smaller magnitude given prices that are generally less-responsive than natural gas prices to changes in demand, coupled with the fact that coal and other fuels (e.g., nuclear) are not as widely used as natural gas in other sectors of the economy outside of the power sector.

order effect' to be more than $25/MWh averaged over 2007–2016 in all three ISO regions, and significantly lower in the states south of the PJM region. The natural gas and wholesale electricity price suppression effects are lowest in 2016.

As mentioned earlier, these natural gas and wholesale price reductions represent a transfer of wealth from natural gas producers and electricity generators to gas and electricity consumers, respectively. Moreover, these price suppression effects are anticipated to decline over time, as supply adjusts to the new demand conditions (Barbose et al. 2016).

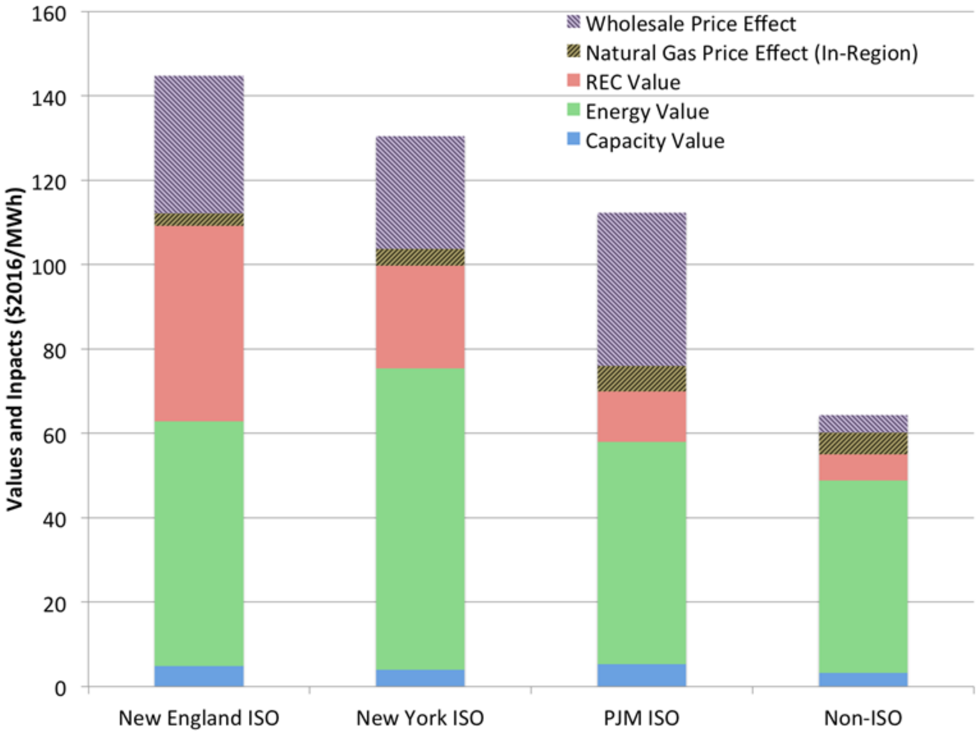

Figure 7. Median energy, capacity, and REC value along with the in-region natural gas price effect and wholesale electricity price effect averaged over 2007-2016

4.2 Approaches to Increase Value

In addition to the core analyses described above, we also explored several ways to enhance the value of offshore wind (see Mills et al. 2018 for additional details). For example, we found that interconnecting to a more-distant but higher-priced interconnection point—e.g., switching from PJM or ISO-NE nodes to NYISO nodes around Long Island—can increase the net value of offshore wind by as much as $25/MWh-wind, even when considering the additional cost of transmission. Similarly, having more than one interconnection point and arbitraging between them can also enhance value by enabling opportunistic sales into higher-priced interconnection points. Selling RECs into a different state than the one in which the project interconnects can also boost value, by as much as $20/MWh depending on the location. Adding battery storage sized (in MWh terms) at roughly one fourth of the offshore wind project capacity[2] can boost value (mostly energy value, but some capacity value) by up to $3/MWh-wind (with a breakeven cost of storage of $250/kWh in some regions, which is below the recent cost of storage), with still-greater incremental value as battery size increases. Finally, wind turbine design (i.e., rotor size and tower height) is found to have a minor effect on market value, at least for this historical marginal analysis.[3]

4.3 Comparing Value to Cost

With little offshore wind deployment in the United States, cost estimates are—to a degree—speculative. The National Renewable Energy Laboratory estimates the levelized cost of energy (LCOE) of a reference offshore wind project installed in the U.S. in 2015 at $180/MWh (Mone et al. 2017), comparable to early cost signals from U.S. projects (Musial et al. 2017). The historical market value estimates presented earlier—if restricted to energy, capacity and RECs, and excluding natural gas and wholesale electricity price suppression—are below this level. Recent tenders in Europe, however, suggest rapid and steep cost reductions for projects planned for installation in the 2020 to 2025 timeframe, with prices at roughly $70/MWh inclusive of needed transmission expenditure (Musial et al. 2017). The historical market value estimates presented earlier, depending on the location and timeframe, span this figure.

Of course, just as the market value of offshore wind varies spatially, so too does LCOE, affected by wind speed, ocean depth, distance from shore, and many other considerations. In two linked studies, Beiter et al. (2017) and Beiter et al. (2016) estimate the LCOE of potential offshore wind projects along the eastern seaboard, taking such considerations into account and projecting future costs in 2022 and 2027. Figure 8 compares these LCOE estimates for 2022 with the historical market value estimates presented earlier to help identify project locations that best-balance cost and system value. We find that the most attractive sites from this perspective are located near southeastern Massachusetts and Rhode Island, while the least attractive are far offshore of Florida and Georgia (Figure 8).

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[2] The size of the battery in this analysis is based on a recent announcement of a partnership between an offshore wind developer (Deepwater Wind) and Tesla to install a 40 MWh battery along side a 144 MW wind plant. Based on other Tesla batteries, we assume that this battery could be operated at full capacity for four hours (i.e., a 10 MW nameplate battery with 4 hours of storage). https://www.utilitydive.com/news/deepwater-tesla-to-pair-offshore-wind-farm-with-40-mwh-battery-storage-sys/448364/

[3] Altering the rotor size and increasing the tower height can lead to a flatter production profile relative to wind with a smaller rotor and lower tower. With high wind penetration, flattening the production profile of wind increases the value by shifting power away from periods that would otherwise have high wind and low prices (Hirth and Müller 2016). At low penetration, the effect of flattening the profile is ambiguous, as it may either shift wind power out of high priced periods or shift it out of low priced periods. Overall, we found no substantial sensitivity of the value to rotor size and hub height, though our analysis was conducted on a marginal basis for, in effect, the first offshore wind plants.

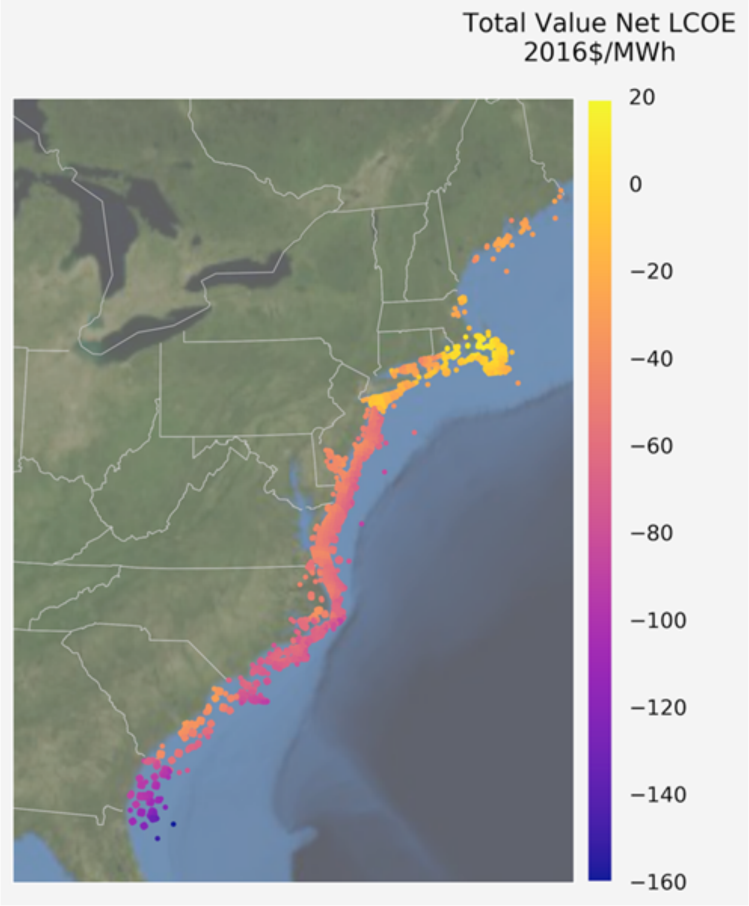

Figure 8. Net value measure of offshore wind (to be used only to rank sites)

5. Conclusions and Future Outlook

We find that the historical, marginal market value of offshore wind varies significantly by project location, and is highest for sites off of New York, Connecticut, Rhode Island, and Massachusetts. The historical market value of offshore wind can be approximated by the value of a flat block of power: locational variations are driven primarily by differences in average energy (and REC) prices. Diurnal and seasonal generation profiles do matter, but mostly differentiate offshore sites based on their capacity value, which is, at least historically, a small component of overall value. The market value of offshore wind also varies significantly from year to year, driven primarily by changes to energy and REC prices, and is lowest in the most recent year analyzed, 2016. Offshore wind reduces air emissions that are harmful to human health and the environment; emissions reductions vary by region, and have declined over time. Wholesale electricity and natural gas price reductions attributable to offshore wind can be substantial, though these price reductions represent a transfer from producers to consumers and are generally expected to decline over time, as supply adjusts to the new demand conditions.

The energy and capacity value of offshore wind in all three ISOs exceeds that of onshore wind, confirming previous research. These value differences are due to offshore wind being located more favorably in terms of pricing points, and also to a more-favorable temporal profile of electricity production. Yet, the cost of offshore wind is also higher than onshore wind, requiring important tradeoffs. Cost reductions that approximate those witnessed recently in Europe may be needed for offshore wind to offer a credible economic value proposition on a widespread basis. Finally, we find multiple ways to enhance the value proposition for offshore wind, including interconnecting to more-distant but higher-priced locations, having more than one interconnection point and arbitraging between them, selling RECs into a different state than the one in which the project interconnects, and adding storage.

Though the historical perspective taken in this study is instructive in identifying key value drivers for offshore wind, the decision to build offshore wind going forward will depend on expectations of future benefits, which may differ from recent historical experience. Additional research to explore how various value factors may change in the future is warranted, yet any such findings would be highly uncertain. Energy value—the largest value component within our analysis—will partly depend on the future direction of natural gas prices, which is uncertain: EIA projects gas prices to drift higher out to 2050 (EIA 2017), while NYMEX natural gas futures suggest flat prices out to 2030. Increasing wind penetration over time could drive down wind's energy value, as the market becomes saturated with low marginal-cost generation during windy times; such a value decline has been observed in high-penetration wind markets and studies internationally (Hirth 2013; Mills and Wiser 2014; Ederer 2015). REC prices—another significant contributor to offshore wind's value—will depend in part on the cost and value of alternative means of complying with RPS requirements, as well as on any specific offshore wind policy obligations. Offshore wind's capacity value depends on capacity prices, the rules for how capacity credit is determined, and whether offshore wind is eligible to participate. Capacity prices are generally expected to increase in the future (Exeter 2014; Frayer and Roumy 2015; Hibbard et al. 2015; Hornby et al. 2015; Exeter 2016; NY DPS 2016; PJM 2016; Dominion 2017; Schatzki and Llop 2017), but several proposed wholesale market reforms may make it more difficult for offshore wind to participate in capacity markets (Grace et al. 2017). Finally, avoided emissions may vary based on future fossil fuel prices and changes to emissions regulations.

Given these uncertainties, future research should target improved understanding of the factors driving value differences, with relatively less focus on the exact magnitude of any particular result. Ultimately, energy markets are uncertain. Research can inform market and policy decisions, but cannot eliminate fundamental uncertainties on how the future will unfold.

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