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Health and climate benefits of offshore wind facilities in the Mid-Atlantic United States

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Abstract

Electricity from fossil fuels contributes substantially to both climate change and the health burden of air pollution. Renewable energy sources are capable of displacing electricity from fossil fuels, but the quantity of health and climate benefits depend on site-specific attributes that are not often included in quantitative models. Here, we link an electrical grid simulation model to an air pollution health impact assessment model and US regulatory estimates of the impacts of carbon to estimate the health and climate benefits of offshore wind facilities of different sizes in two different locations. We find that offshore wind in the Mid-Atlantic is capable of producing health and climate benefits of between $54 and $120 per MWh of generation, with the largest simulated facility (3000 MW off the coast of New Jersey) producing approximately $690 million in benefits in 2017. The variability in benefits per unit generation is a function of differences in locations (Maryland versus New Jersey), simulated years (2012 versus 2017), and facility generation capacity, given complexities of the electrical grid and differences in which power plants are offset. This work demonstrates health and climate benefits of offshore wind, provides further evidence of the utility of geographically-refined modeling frameworks, and yields quantitative insights that would allow for inclusion of both climate and public health in benefits assessments of renewable energy.

Introduction

Use of fossil-fuel derived electricity contributes to two major public health issues—climate change and air pollution (Haines *et al* 2009, Markandya *et al* 2009, IPCC 2014, Watts *et al* 2015), with climate change primarily caused by CO_2 emissions (as well as leaked CH_4) and health impacted by emissions of SO_2, NO_x, $PM_{2.5}$, and other pollutants. Climate change will likely be the greatest public health threat in the 21st century, impacting health in ways ranging from sea level rise and displacement, to increasing air pollution, to impacting water security and both food security and nutrition (IPCC 2014, Myers *et al* 2014, Watts *et al* 2015). The health burden of air pollution from electricity generation in 2010 is estimated at 460 000 deaths worldwide, and approximately 17 000 in the US (Lelieveld *et al* 2015). Reducing reliance on fossil-derived electricity can mitigate both of these issues related to fossil fuel combustion, and therefore have benefits for both public health and the climate (Markandya *et al* 2009, Watts *et al* 2015).

Energy efficiency and renewable energy (EE/RE) are capable of producing benefits to the environment and public health by displacing electrical generation sources that emit greenhouse gases (GHGs) or other air pollutants, as well as by having impacts across the full life cycle of electrical generation (Jaramillo *et al* 2007, Epstein *et al* 2011). Many recent studies evaluated the benefits of EE/RE projects (Gilmore *et al* 2006, 2010, Thompson *et al* 2009, 2011, Weber *et al* 2010, Budischak *et al* 2013, Siler-evans *et al* 2013, Plachinski *et al* 2014, Buonocore *et al* 2015, Wiser *et al* 2016). These studies found that these projects can have substantial benefits, and that the benefits of different EE/RE projects can vary dramatically by type and location due to a variety of factors, including local electrical grid infrastructure, constraints, and electrical market conditions, and the conditions of the local and regional power plant fleet, including power plant efficiency, fuel type, emissions rate, and populations downwind. This high variability demonstrates that there is substantial value in evaluating benefits in a site-specific manner, especially given that EE/RE programs vary greatly in their diurnal and seasonal profiles.

Previous studies examined the benefits of onshore wind, solar photovoltaic (PV), and demand side management (DSM). However, none of these studies have evaluated the climate and health benefits of offshore wind. Offshore wind is becoming an established source of renewable energy in Europe, which had 5.4 GW installed capacity in 2012 (International Energy Agency 2013). Offshore wind could have a substantial role in the US energy mix, with an estimated potential capacity in the US of 4200 GW (Lopez *et al* 2012). Offshore wind in the east coast of the US generally coincides with peak demand, and is estimated to be able to fulfill approximately one-third of electrical demand for the entire east coast of the US (Dvorak *et al* 2013). Despite the large resource availability, this energy source is in the beginning stages of development in the US. The slow development of this resource is possibly due to a variety of factors, ranging from high upfront costs, difficulties with permitting and obtaining power purchase agreements, lack of necessary infrastructure for construction, and uncertainties around applicable regulations and incentives, such as renewable portfolio standards and production tax credits (Musial and Ram 2010). There are currently no operating offshore wind facilities in North America, but there are several in the development stages, especially off the Atlantic Coast. Construction of the first US offshore wind facility, Deepwater Wind's Block Island project in Rhode Island, began in the summer of 2015, with a planned capacity of 30 MW (US Energy Information Administration 2015). In Massachusetts, offshore wind development areas have already been leased to three companies, with potential total capacity over 6000 MW (US Bureau of Offshore Energy Management 2015a). In addition, areas off the coasts of Delaware, Maryland and New Jersey have been leased (US Bureau of Offshore Energy Management 2015b, 2015c, 2015d).

Here, we use the Electrical Policy Simulation Tool for Electrical Grid Interventions, or the EPSTEIN model (Buonocore *et al* 2015), to estimate the climate and health benefits of different sizes of offshore wind projects off the coast of New Jersey and Maryland. We use 2017 to represent a future implementation year, and simulate different sizes of projects, which allows for examination of whether the relationship between project size and total benefits is linear. Additionally, we do two simulations using 2012 as a simulation year to facilitate comparing offshore wind to onshore wind, solar PV and two different types of DSM, based on a previous study (Buonocore *et al* 2015).

Methods

We developed offshore wind project scenarios that reasonably bound the possible size of an offshore wind facility in each location, along with baseline scenarios without any offshore wind. Offshore wind generation output was calculated hourly based on the Weather Research and Forecasting (WRF) model for wind speeds offshore. To estimate benefits of different sizes, and to simulate the health and climate benefits, we used the EPSTEIN model (Buonocore *et al* 2015) for the Eastern Interconnect. The EPSTEIN model links an electrical grid simulation model that provides electrical generation and emissions of NO_x, SO_2, and CO_2 for electrical generation units (EGUs) on the Eastern Interconnect (Buonocore *et al* 2015). Carbon emissions are valued using the social cost of carbon established by the US Federal Government (US Govt. 2013), and the monetary value of health impacts from NO_x and SO_2, due to formation of $PM_{2.5}$, are estimated using a health impact assessment model that provides site-specific impact estimates (Buonocore *et al* 2014).

Scenario development and generation estimates

We developed scenarios that provide reasonable estimates for possible offshore wind projects in each location. For New Jersey, the capacity numbers correspond approximately with the minimum offshore wind capacity called for in the New Jersey Energy Master Plan for 2012 and 2020 (1100 MW and 3000 MW, respectively). For Maryland, the 200–400 MW capacity numbers reasonably correspond with scenarios under consideration in nearby Delaware, while 1000 MW represents a scenario under consideration in Maryland. This region has average offshore wind speeds between 8 and 9 m s^{-1} at a height of 90 m and power densities around 700–800 W m^{-2}, so using RePower 5 M 5 MW turbines, capacity factors for generation around 40%–45% are possible in this area (Jonkman *et al* 2009). Scenarios are described in table 1.

We use estimated hourly generation based on runs of the WRF model for 2010 and 2011 (Dvorak *et al* 2013), and the power curve of the RePower 5 M 5 MW turbine. We simulate the New Jersey facility as being connected to the PJM-MidE transmission area and the Maryland facility being connected to PJM-SW. With array losses of 10% and transmission loss of 1.5%, the average annual capacity factors in both cases are 36% (Jonkman *et al* 2009, Dvorak *et al* 2013).

Electrical dispatch model

To simulate the generation and emissions displaced by the EGUs on the Eastern Interconnect, we use Market Analytics, under license from Ventyx (Ventyx/ABB 2012). The Market Analytics model uses the PROSYM engine to produce optimized unit

Table 1. Annual generation and benefits of offshore wind scenarios, with comparison to onshore wind scenarios from Buonocore *et al* (2015). Values are rounded to two significant figures and sums may not add due to rounding.

Scenario (year—capacity location)	Total generation per year (GWh)	Total benefit per year (million $)	Total benefits ($/MWh)	Total SO_2 benefit per year (million $)	SO_2 benefits ($/MWh)	Total NO_x benefit per year (million $)	NO_x benefits ($/MWh)	Premature deaths avoided per year	Total CO_2 benefit per year (million $)	CO_2 benefits ($/MWh)
Offshore wind scenarios, 2017 implementation year										
2017—1100 MW New Jersey	3700	200	54	75	20	20	5.3	13	100	28
2017—3000 MW New Jersey	10 000	690	68	340	34	54	5.3	55	290	29
2017—1000 MW Maryland	3200	240	73	110	35	20	6.1	18	100	32
2017—200 MW Maryland	650	75	120	44	69	9.1	14	7	22	34
2017—300 MW Maryland	970	82	84	44	45	8.9	9.2	7	29	30
2017—400 MW Maryland	1300	92	71	44	34	9.8	7.6	7	38	29
Offshore wind scenarios, 2012 implementation year										
2012—1000 MW Maryland	3100	370	120	220	71	29	9.3	35	120	38
2012—1100 MW New Jersey	3600	360	100	190	53	40	11	32	130	37
Onshore wind scenarios from Buonocore *et al* (2015)										
2012—500 MW Northern Ohio	1300	180	150	110	88	18	14	18	54	43
2012—500 MW Chicago Area	1400	210	150	140	95	14	9.4	21	60	42
2012—500 MW Cincinnati Area	1300	210	170	140	110	19	15	22	53	42
2012—500 MW Eastern PA	1400	110	81	60	43	11	8.1	10	43	31
2012—500 MW Southern NJ	1000	110	110	70	69	8.6	8.6	11	31	31
2012—500 MW Virginia	1200	100	91	58	51	9.8	8.5	9	37	32

commitment and dispatch decisions. Market Analytics simulates the behavior of the electrical market by providing zonal locational market-price-forecasting, including energy and operating reserves markets with EGU-specific operational data, including ramp rates, minimum up and down times, multiple capacity blocks, and variable generation capacity from renewables and hydroelectricity. It is a security-constrained chronological dispatch model that produces hourly electricity prices for each zone, informed by hourly loads, market rules, and EGU-specific constraints. This chronological approach accounts for time dynamics, including transmission constraints and operating characteristics of EGUs, such as minimum downtime for maintenance, and constraints on electrical transmission. The model includes regulations on NO_x and SO_2 emissions, participation in the regional GHG initiative as appropriate, but no Federal regulation on CO_2.

Our analysis was based on default data from Market Analytics, which includes data from the US Energy Information Administration, US EPA, North American Electric Reliability Corporation and the Federal Energy Regulatory Commission, Ventyx's professional judgment, and trade press announcements. Hourly load shapes are provided by Ventyx, adjusted annually based on utility and ISO/RTO forecasts of regional energy and peak load growth. However, we included several updates to the dataset, including transmission path capacity across PJM to account for transmission improvements required by Renewable Portfolio Standards, forecasted new gas plants, and updated emissions rates based on data reported to the US EPA (Buonocore *et al* 2015).

Public health impact assessment model

To estimate the monetary value of the health impacts of SO_2 and NO_x emissions for each EGU on the Eastern Interconnect, we used a previously published statistical model (Buonocore *et al* 2014). This statistical model was developed using a series of simulations of the Community Multiscale Air Quality (CMAQ) model, designed to produce source-specific estimates for a set of EGUs on the PJM Interconnection for the influence of SO_2 and NO_x on annual average $PM_{2.5}$ concentrations, the main health impact of SO_2 and NO_x emissions. CMAQ is a complex atmospheric fate, chemistry, and transport model that is used by the EPA for regulatory applications, and for air quality and health impact assessment (Byun and Ching 1999, Roy *et al* 2007, Brown *et al* 2011, von Stackelberg *et al* 2013). These $PM_{2.5}$ concentrations, secondarily formed from the SO_2 and NO_x emissions, were then linked to data on exposed population and baseline mortality rate, and the excess mortality due to $PM_{2.5}$ was estimated using a concentration-response function of a 1% increase in mortality per 1 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ concentrations (Roman *et al* 2008, Buonocore *et al* 2014). Monetized estimates of health impact per ton emitted of SO_2 and NO_x, due to health impacts of secondarily-formed $PM_{2.5}$, were extrapolated to unmodeled EGUs based on the geographical distribution of population around the source. The health impacts were then monetized using a value of statistical life (VSL) of US$7.58 million, 2012 USD (Dockins *et al* 2004). The impact/ton values of SO_2 from this model are similar to those previously reported, after accounting for differences in concentration-response function and mortality risk (Fann *et al* 2009). The impact/ton values for NO_x in this model are slightly higher than those previously reported in many studies, largely due to the effect that NO_x emissions have on amplifying sulfate formation, which is captured by the version of CMAQ used in our study (Buonocore *et al* 2014).

To facilitate comparison between scenarios and to examine drivers behind differences in benefits, we report total facility benefits and benefits per MWh of electricity generated for each emitted pollutant and in total across emission types.

Results

Benefits to public health and the climate from hypothetical offshore wind installations varied by an order of magnitude across scenarios, with the annual benefits ranging from $75 million for the smallest installation to $690 million for the largest (table 1). Generally, benefits attributable to avoided SO_2 emissions were highest, followed by those attributable to avoided CO_2, and then NO_x. For the installations with two simulated years, the benefits are lower for future years due to the electric system having lower emissions in 2017 than 2012.

As expected, benefits do increase with the size of the installation, but they do not scale linearly, and the increase in benefits relative to the increase in installation size varies by location (table 1). For example, the 3000 MW installation off the coast of New Jersey generates 2.7 times more electricity than the 1100 MW installation, but the total benefits increase by a factor of 3.45. Benefits from SO_2 reductions increase by a factor of 4.5, benefits from NO_x reductions increase by a factor of 2.7, and benefits from CO_2 reductions increase by a factor of 2.9. Conversely, the 400 MW installation off the Maryland coast generates twice as much electricity as the 200 MW installation, but the total benefits only increase by 23%. Benefits from SO_2 reductions stay nearly the same, benefits from NO_x reductions increase by around 8%, and benefits from CO_2 reductions increase by 73%. Comparing the 400 and 1000 MW installations (an increase in electricity generation by a factor of 2.5), the total benefits increase by a factor of 2.6, benefits from SO_2 reductions increase by a factor of 2.5, benefits from NO_x

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Table 2. Annual generation and emissions avoided for offshore wind energy scenarios. Values are rounded to two significant figures and sums may not add due to rounding.

Scenario (year—capacity location)	Total generation per year (GWh)	Total SO_2 benefit per year (1000 tons)	SO_2 emissions avoided (lb/MWh)	Total NO_x benefit per year (1000 tons)	NO_x emissions avoided (lb/MWh)	Total CO_2 benefit per year (1000 tons)	CO_2 emissions avoided (lb/MWh)
2012—1100 MW New Jersey	3600	11.5	6.4	3.1	1.7	2800	1500
2017—1100 MW New Jersey	3700	2.44	1.3	1.4	0.7	2200	1200
2017—3000 MW New Jersey	10 000	12.0	2.4	3.7	0.7	6100	1200
2012—1000 MW Maryland	3100	10.1	6.4	1.9	1.2	2500	1600
2017—1000 MW Maryland	3200	3.95	2.4	1.4	0.8	2200	1400
2017—200 MW Maryland	650	1.47	4.6	0.6	1.9	460	1400
2017—300 MW Maryland	970	1.45	3.0	0.6	1.2	610	1300
2017—400 MW Maryland	1300	1.47	2.3	0.7	1.0	800	1200

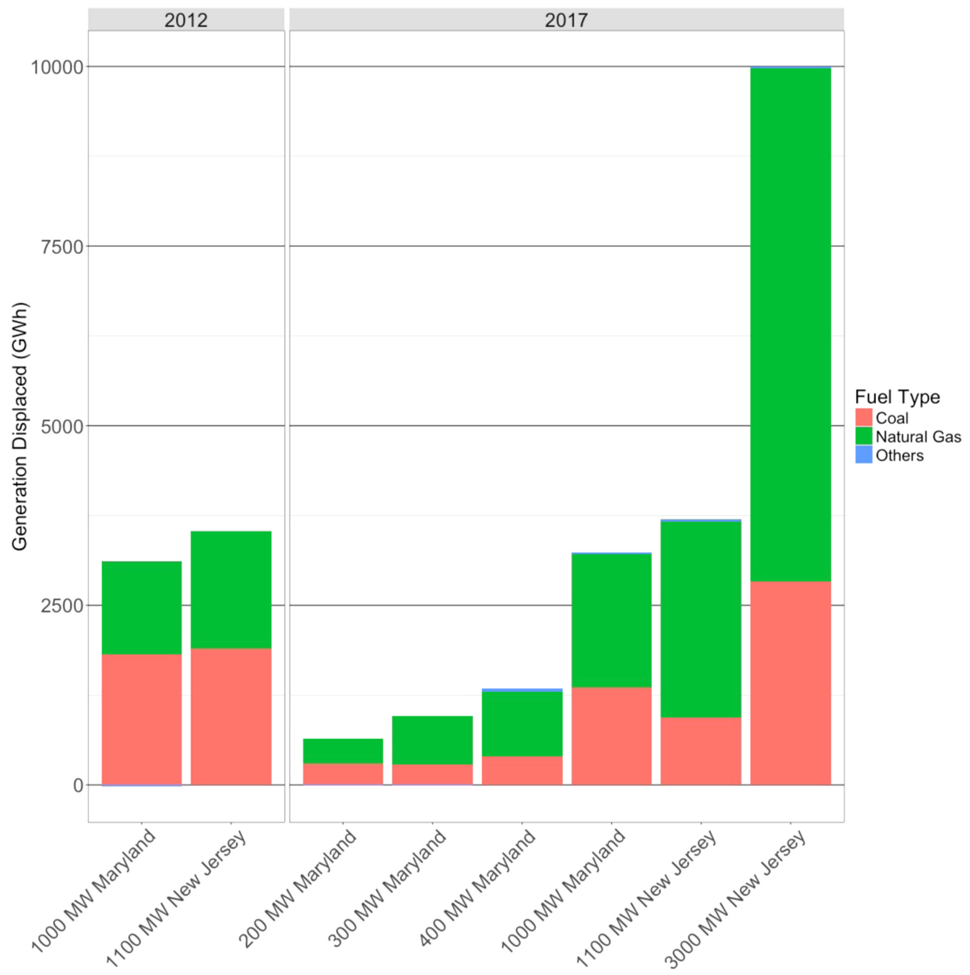

Figure 1. Generation types offset by offshore wind installation location, size, and year.

reductions increase by a factor of 2, and benefits from CO_2 reductions increase by a factor of 2.6 (table 1).

Health and climate benefits per MWh of electricity generated were between \$54 and \$120 (table 1). Variability is based on facility size, geographic location, and simulated year (2012 versus 2017). For example, comparing the 3000 MW installation off the New Jersey coast to the 1100 MW installation, benefits per MWh increase, largely due to a factor of 1.7 increase in SO_2 emissions averted per MWh (table 2). Comparing the 400 MW installation off the coast of Maryland to the 200 MW installation, the benefits per MWh decrease from \$120/MWh to \$71/MWh (table 1), given essentially no reductions in SO_2 and minimal reductions in NO_x between the two scenarios. Benefits per MWh for the 400 MW installation off the Maryland coast are fairly similar to those of the 1000 MW installation, except for NO_x, which decreased by around 20%.

Coal and natural gas are the main types of generation affected by each installation, and the proportions of each fuel type displaced vary depending on location, size, and year (figure 1). For the 1000 MW installation off the coast of Maryland and the 1100 MW installation of the coast of New Jersey, the proportions of coal versus natural gas displaced differ by year. In both locations, more coal is displaced in 2012 than in 2017. In 2017, the 200, 300, and 400 MW installations off the coast of Maryland displace similar amounts of coal, with natural gas being displaced as facility size increases, but the amount of coal generation displaced by the 1000 MW facility is substantially higher.

Comparisons in benefits across scenarios generally follow the trends in generation, generation mix, and emissions displaced (figure 2, table 1). For the 2012 scenarios, the Maryland facility had slightly higher benefits than the New Jersey facility did (figure 2, table 1). This is largely explained by higher proportionate displacement of coal (figure 1) and the proportionately higher impacts of the SO_2 from coal plants displaced (figure 2). For 2017, total benefits tended to scale with total generation, and with displaced generation from coal.

Under all scenarios, the generation displaced is a mixture of small changes distributed across many plants, and a few plants experiencing larger displacements, but the mixture varies among scenarios (table 3). The percentage of total generation displacement from plants contributing less than 1% of the total generation displacement ranges from 22% in the 2017 scenario with a 200 MW facility off the coast of Maryland, to 52% in the 2012 scenario with a 1000 MW facility off the

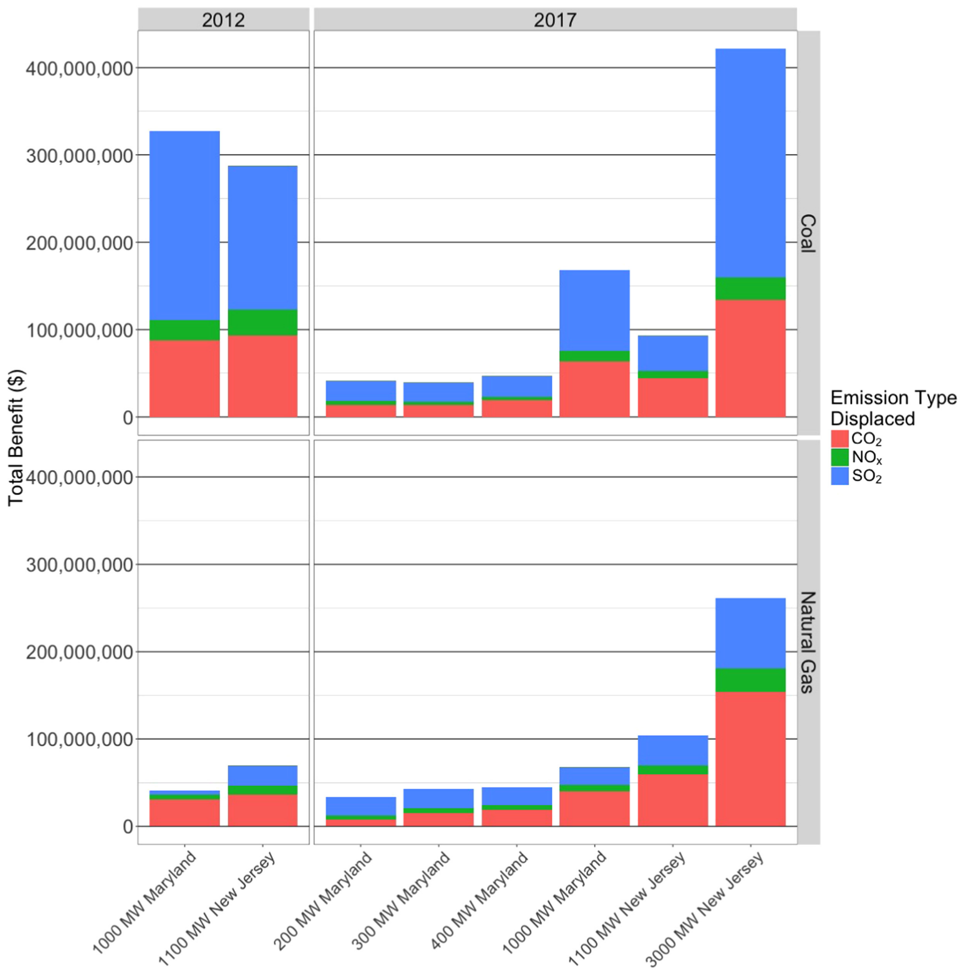

Figure 2. Monetized public health and climate benefits of different offshore wind scenarios, by impact type and fuel type.

Table 3. Total percentage of annual displaced generation coming from plants contributing less than 1% or more than 5% of the total generation displaced by each installed facility, for each offshore wind scenario.

Scenario	Percentage of total displaced generation coming from plants contributing less than 1% to total displaced generation	Percentage of total displaced generation coming from plants contributing more than 5% to total displaced generation
New Jersey—2012 1100 MW	43	0
New Jersey—2017 1100 MW	39	7.4
New Jersey—2017 3000 MW	35	5.5
Maryland—2012 1000 MW	52	29
Maryland—2017 1000 MW	36	16
Maryland—2017 200 MW	22	56
Maryland—2017 300 MW	27	46
Maryland—2017 400 MW	40	21

coast of Maryland. The percentage of total generation displacement from plants contributing over 5% of the total generation displacement ranges from 0% in the 2012 scenario with the 1100 MW facility off the coast of New Jersey, to 56% in the 2017 scenario with the 200 MW facility off the coast of Maryland. The larger facilities tended to have a higher proportion of generation displacement coming from smaller displacements distributed across many sources.

Discussion

There was substantial variability among the total benefits and the benefits per unit generation of different offshore wind facilities simulated in Maryland and New Jersey. Notably, total benefits per unit generation varied among facilities in the same location with the same physical attributes, where the only differences were related to generation capacity. This indicates that the relationship between total benefits and generation is not linear, an assumption that is often implicitly made in models that provide estimates of health benefits per unit generation. This can be explained by facilities with different capacities displacing varying proportions of coal and natural gas, and consequently, differing proportions of benefits coming from each displaced emission type.

The 2017 results in particular illustrate some interesting dynamics in the relationship between benefits and the generation capacity of a facility. The 200, 300, and 400 MW facilities in Maryland all displace approximately the same amount of coal, with most of the change in fuel displaced coming from natural gas (figure 1). The generation displacement also comes from a fairly high proportion of large individual contributors (table 3). However, the 1000 MW Maryland facility displaces proportionately much more coal than the 400 MW facility, and a lower proportion from plants contributing over 5% to the total displaced generation (figure 1, table 3). This may indicate a 'threshold' effect, where the smaller offshore wind facilities can displace one coal generating source (or sources), and the 1000 MW facility is able to displace a larger set of sources, with little space in between. This could be due to the additional generation of the 1000 MW facility, making a coal-fired power plant (or set) no longer economical to commit to generate in the day ahead unit-commitment, whereas it was economical to commit the day ahead with the 400 MW facility in place. Because coal plants in particular are constrained by relatively high minimum operating levels and long start-up times, additional generation may need to meet some threshold value to push an older fossil fuel unit entirely offline in the day-ahead scheduling done by system operators. Similarly, comparing the two facilities in New Jersey, the 3000 MW facility displaces proportionately less coal than the 1100 MW facility (figure 1), mostly from small contributors (table 3). However, the benefits per MWh of the 3000 MW facility are higher than the 1100 MW facility, largely from an increase in benefits from displaced SO_2 per MWh. This is explained by the 3000 MW facility displacing much more SO_2 per MWh, indicating that the larger facility displaces coal generation with higher SO_2 emissions that the smaller facility does not displace.

Our benefits per MWh estimates for offshore wind are fairly similar to those previously found for onshore wind in the Eastern US along with baseload DSM and solar PV (Buonocore *et al* 2015, table 1). The amount of variability among different sizes of offshore wind facilities is similar to the amount of variability among different locations of baseload DSM, onshore wind, and solar PV on the same power grid region. The differences in total benefits and benefits per MWh provide further reinforcement for the idea that the location of a renewable energy installation is an important determining factor for total benefits, and that the location with the highest generation may not necessarily be the one with the highest benefits (Siler-evans *et al* 2013, Buonocore *et al* 2015). Our results add an additional important complexity—benefits may not linearly scale with the generation capacity of the facility, so relative benefits between different locations or installation types may vary if different facility sizes are compared.

Even though our modeling framework includes electrical grid dynamics and power plant specific emissions and impacts, it has some limitations. Our modeling framework only includes SO_2, NO_x, and CO_2 emissions from power plants, and does not include emissions of primary $PM_{2.5}$, mercury, carbon monoxide, methane, nitrous oxide, and other compounds. However, the three substances we did include tend to dominate estimates of impact of fossil fuels and benefits of renewable energy installations (Epstein *et al* 2011, Siler-evans *et al* 2013, Buonocore *et al* 2015). Our modeling framework does not account for possible seasonal or temporal differences in impact per ton emitted or possible differences in emissions due to power plants cycling up and down due to higher electrical load variability. However, these are not likely to substantially affect our estimates (Katzenstein and Apt 2009, Weber *et al* 2009, 2010, Valentino *et al* 2012, Plachinski *et al* 2014). Our model also does not take into account full life cycle impacts of the displaced fuels, including health impacts of coal mining and waste disposal, or possible methane leaks and health impacts related to the extraction of unconventional natural gas (Epstein *et al* 2011, Adgate *et al* 2014, Brandt *et al* 2014). Our choice of values for the social cost of carbon likely also represents a lower bound on the impacts due to climate change (Arrow *et al* 2013, Moore and Diaz 2015), however the implications of higher social costs of carbon can be explored by linearly scaling. Additionally, our model makes parametric choices for the concentration-response function relating $PM_{2.5}$ exposure and mortality, and also for the VSL, which have uncertainties (Dockins *et al* 2004, Roman *et al* 2008, Buonocore *et al* 2014). As for the social cost of carbon, the implications of alternative values for these parameters can be explored by linearly scaling, and formal uncertainty analysis around these key parameters could be conducted, although this would not change our central conclusions regarding the magnitude of variability across offshore wind model scenarios. Finally, our quantitative estimates are dependent on the base year selected and the corresponding fuel prices and regulatory scenarios, and may change if future offshore wind patterns are substantially different from those used as inputs here.

Despite these limitations, our work provides some useful additions to the understanding of the health and climate benefits of renewable energy. Our work is the first—to our knowledge—assessment of the health and climate benefits of offshore wind, and demonstrates that offshore wind can have benefits to climate and health that are similar to onshore wind. We show that like onshore wind, offshore wind is also capable of displacing coal given current fuel prices, which tends to increase total benefits (Buonocore *et al* 2015), although patterns of displacement may differ since offshore wind resource in this region tends to be more coincident with peak loads (Dvorak *et al* 2013). Also, like onshore wind, we show that offshore wind has total health and climate benefits fairly similar to its market cost, using a value of the social cost of carbon that is likely an underestimate. Another way of describing that is that the entire cost of an offshore wind facility would be justified in the health and carbon benefits, before considering the value of selling the electricity. For all offshore wind scenarios, the health benefits are between $25 and $83 per MWh, climate benefits are between $28 and $38 per MWh, and total benefits are between $54 and $120 per MWh. For comparison, the US Department of Energy and National Renewable Energy Laboratory estimate that the levelized cost of offshore wind is between $100 and $200 per MWh (US Department of Energy 2016). While a comprehensive energy choice model would need to compare the costs and benefits with corresponding values for other technologies, these estimates reinforce the importance of including health and climate benefits. Additionally, our work demonstrates that the relationship between facility size and total benefits is not linear. This again illustrates the complex, nonlinear nature of the electrical grid, and the importance of site-specific and facility-specific modeling exercises (Siler-evans *et al* 2013, Buonocore *et al* 2015).

This study, and others like it which analyze health and climate benefits of EE/RE projects, are also useful in the context of life cycle assessments (LCA) of electricity generation. Standard attributional LCAs are able to calculate impacts of energy sources, compare impacts of different fuel sources or fuel mixes, and examine sensitivity to key parameters (Weinzettel *et al* 2009, Earles and Halog 2011, Dolan and Heath 2012). However, analyses such as the one presented here are able to put these comparisons into a more consequential LCA framework, which is able to account for environmental impacts, and also the benefits that occur through economic interactions (Earles and Halog 2011), and do so including time- and location-specific parameters. This level of detail is important for making accurate assessments of benefits, doing comparisons fairly and accurately, and can feed into project-specific consequential LCAs.

This paper further reinforces that renewable energy can have benefits to climate by reducing GHG emissions, and to public health by reducing air pollutant emissions from fossil-fueled power plants and improving air quality. Including both climate and health benefits is important since it may be a useful lever for policy. Climate change has been called one of the greatest public health opportunities of the 21st century, since methods to mitigate climate change generally carry co-benefits to health (Watts *et al* 2015). Since these co-benefits are often local and near-term, they can carry a lot of weight in policy and other decision-making (Driscoll *et al* 2015, Watts *et al* 2015). Therefore, using methods to estimate health benefits of climate mitigation measures allows public health be included in decision-making around climate mitigation, and may provide additional encouragement for climate mitigation.

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