Title: Emissions reduction benefits of siting an offshore wind farm: a temporal and spatial analysis of Lake Michigan

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Abstract

Siting decisions of offshore wind farms can influence the magnitude of emissions reduction benefits. This paper calculates electricity generation and emissions reduction of CO₂, NO_x, and SO₂, and values these reductions to determine the impact of the siting location for a 300 MW offshore wind farm in Lake Michigan. The most important patterns for emissions reduction were the monthly trends, where January, March, and December consistently had the highest electricity generation and emissions reduction benefits. Summer months such as July and August had the lowest emissions reduction benefits. The intra-day trends showed higher emissions reduction benefits during off-peak hours, due to a higher likelihood of coal units being the marginal generator. These diurnal differences were smaller in magnitude than the seasonal differences. Two benefit valuation scenarios were analyzed for a 20 year time period, one using marginal damages of pollution and a second using market prices for pollution allowances. The first scenario resulted in emissions reduction benefits ranging from \$1,827/kW to \$2,690/kW (\$2,508/kW averaged) throughout the Lake Michigan region for the 20 year period (applying a 3% discount rate). This equates to approximately \$33/MWh in all lake locations since the emissions reduction benefits are primarily a function of electricity generation. The market price scenario resulted in a much lower range of \$820/kW to \$1,060/kW (\$987/kW average or 39% of the pollution damage costs). In scenario 1, the major component of emissions reduction benefits was CO₂ reduction (86% of benefits), and 83% of these CO₂ benefits were from offsetting coal plant emissions. A sensitivity analysis on size and region of emission reduction location showed that the NO_x and SO₂ benefits vary significantly (unlike CO₂ benefits), but this variation had minimal effects on the total emissions reduction benefits. In comparison with economic investment costs, the scenario 1 emissions reduction benefits equal 49% of the total investment cost (in 2014 \$million) on average. Spatial maps and heat maps are generated to illustrate the spatial and temporal variations in the emissions reduction benefits.

1. Introduction

Renewable energy generation can yield large emissions reduction benefits by displacing coal and natural gas generation, thereby reducing health and environmental impacts. To most effectively implement appropriate renewable energy policies and projects, it is necessary to better characterize public and private costs, which includes valuation of externalities (Borenstein 2011). Currently, the investment cost of renewables (Menegaki 2008), as well as key policy incentives or mandates such as the production tax credit, are key determinants in influencing the deployment of renewable technology and traditional electricity generation for U.S. electric grid modification. While select materials such as iron, cement, or copper may have higher usage in renewable technologies compared to other electricity generation systems, renewable technologies have significantly lower environmental impacts, over their life-cycles, compared to fossil fuel systems (Hertwich, et al. 2015). To analyze potential emissions reduction benefits of one renewable technology, this study quantifies and values the 20 year emissions reduction for siting a 300 MW offshore wind farm (OWF) in Lake Michigan.

The Lake Michigan region was selected for this analysis given its size and the large potential for emissions reduction. For example, renewable energy systems sited in the U.S. Midwest can displace over double the emissions per unit of renewable generation than the same renewable energy system placed in California (Callaway, Fowlie and McCormick 2015) (Sivaraman and Keoleian 2010). The state of Michigan generated about 50% of its net electricity from coal in 2014 (U.S. EIA 2015), and coal fueled 78.7% of the electricity for the 2014 Great Lakes/Mid-Atlantic electricity generation region (U.S. EPA 2014). Since coal creates 1.85 times more CO₂ combustion emissions (per MMBtu produced) than natural gas (U.S. EIA 2015), this region has relatively large emissions impacts and, consequently, large potential emissions reduction benefits. By quantifying these benefits, the results can inform state-level policy decisions as the nation prepares for future emissions reduction regulations such as the Clean Power Plan (U.S. EPA 2015). While other cleaner fossil fuel sources or other renewable energy generation can address goals of the Clean Power Plan, this study looks at the use of offshore wind to meet these criteria since it is currently a large but untapped resource in this country.

In the study, the emission quantification uses EPA's AVERT (AVoided Emissions and geneRation Tool) to calculate the emissions reduction in the power systems due to a 300 MW offshore wind farm. This model's temporal resolution allows for accounting of hourly wind speed variation and hourly variation from electricity generation due to fluctuating demand, and reports CO₂, NO_x, and SO₂ (U.S. EPA 2014). Other publicly available models are either over-simplified, allowing demand changes to impact all plants

instead of only the marginal plants, or too specific, requiring detailed generator specifications and grid infrastructure data (Ryan, Keoleian and Johnson 2016). In addition, this study introduces a new renewable energy generation source, so it cannot integrate dynamic modeling from econometric studies that analyze existing renewable energy generation data (Cullen 2013). The AVERT model uses historical data to generate an hourly emission output and marginal emission factors for the fossil fuel grid mix. However, AVERT does not account for future demand changes and the 2014 grid model is held constant for the 20 year project scope of the OWF in this study (Ryan, Keoleian and Johnson 2016). Despite these limitations, this tool is appropriate for this study since it enables modeling a larger grid area for electricity grid displacement and it enables quantifying the hourly reduction of high cost pollutants. Health and climate benefits resulting from renewable energy projects are currently not characterized with respect to location variations of electrical grid displacement benefits in any single simulation tool (Buonocore, et al. 2016). The AVERT model examines the electricity generation, emission quantification, and emission valuation while using publicly available tools to determine the emissions reduction impact of any OWF siting location in Lake Michigan.

Emissions reduction benefits of NO_x and SO_2 were calculated using the APEEP model (Air Pollution Emission Experiments and Policy) (N. Muller 2011), and CO_2 benefits were estimated using the social cost of carbon (Greenstone, Kopits and Wolverton 2011). Since AVERT only quantifies CO_2 , NO_x , and SO_2 emissions, this study analyzes the monetization of these specific pollutants. Muller values emissions as social marginal damages (of NH_3 , $\text{PM}_{2.5}$, NO_x , SO_2 , VOC, and PM_{10}), with levels of marginal damage varying spatially within the United States. This approach has been used to inform regulations (Muller and Mendelsohn 2009) and to model and illustrate the role of both marginal damages and the market value of permits in environmental cost accounting (Muller, Mendelsohn and Nordhaus 2011). In addition, CO_2 emission reduction are valued as marginal damages using the social cost of carbon (SC- CO_2) values determined by the U.S. government (Greenstone, Kopits and Wolverton 2011). Without any strong regulations for emission regulations or OWF siting guidelines in Michigan, the APEEP model was ideal for valuing NO_x and SO_2 with spatial and marginal cost considerations. The SC- CO_2 was appropriate for assessing CO_2 damage costs (Greenstone, Kopits and Wolverton 2011). In previous work, emissions changes have been valued for new electric vehicles (Holland 2015), but have not been valued for new renewable electricity generation.

This study is the first to analyze the social benefits of an OWF that reduces marginal emissions from the U.S. Midwest grid based on electricity generation calculations, while also considering the geographic

variation of the benefits. This analysis is unique in coupling the (1) engineering calculations of electricity generated from wind speed data with (2) statistical analysis of emissions reduction potential based on actual grid operations and then (3) linking the results to valuation of social benefits. Unlike previous studies which have quantified wind-powered generation into emissions reduction from specific generators (Denny and O'Malley 2006), this study estimates regional U.S. grid emissions impact and further values the emissions reduction as monetary benefits. This paper develops results for electricity generation, emission quantification, and emissions reduction benefits on the Michigan side of the Lake Michigan region.

2. Methods

The framework for this analysis of an OWF consists of three main components: 1) electricity generation, 2) emission quantification, and 3) emissions reduction benefit valuation. The key datasets, results, and linkages between models are illustrated in Figure 1. The analysis is demonstrated for an OWF consisting of 100 3MW Vestas V112 turbines oriented as a 10x10 grid with spacing of 4 rotor diameters from north to south and 7 rotor diameters west to east, a spacing that helps optimize electricity generation performance (Chiang, et al. 2015). These conceptualized OWFs are analyzed at each location throughout the Lake Michigan region for the total emissions reduction benefits. The Vestas V112 turbine was selected to allow us to compare the emissions reduction benefits with earlier work on investment cost (Chiang, et al. 2015). The analysis was performed on an hourly basis for the three dataset years (2004, 2005, 2006) to interpret the hourly and monthly trends. Sensitivity analyses were also conducted to explore the effects of constant electricity generation, larger wind farm size, different emissions reduction regions, and different emissions reduction benefits valuation methods. Final results were compiled annually to determine the spatial trends for the Michigan portion of the Lake Michigan region. The emissions reduction benefits were computed in 2014 \$US and were also analyzed as cost per unit electricity generation (\$/MWh).

Fig. 1: Analytical framework for estimating the emission reduction benefits of an offshore wind farm with shaded boxes indicating final results. Acronyms are as follows: NREL, National Renewable Energy Laboratory; AWS, AWS Truepower; AVERT, AVOIDed Emissions and geneRation Tool; EIA, U.S. Energy Information Administration; EPA, US Environmental Protection Agency; APEEP, Air Pollutions Emission Experiments and Policy.

2.1. Electricity Generation

For the 300 MW OWF, two wind speed data sets, illustrated in Figure 2, were combined with the wind turbine power curve to determine the annual hourly electricity generation in all locations of Lake Michigan. One wind speed dataset was the NREL/AWS continuous annual average wind speed dataset (NREL 2010) that has continuous data in order to site the hypothetical OWFs at every location in Lake Michigan. The second dataset was the NREL Eastern Wind Speed dataset (NREL 2012) that has hourly data at certain locations in Lake Michigan. Both datasets are necessary in providing the spatial and temporal components of electricity generation throughout the entire Lake Michigan region. Additional

details for the electricity generation calculations, such as analysis of the regional differences (north, south, west and east as labeled on Figure 2), can be found in Appendix A.

Fig 2. Two wind speed datasets used in determining hourly electricity generation in all of Lake Michigan: (a) NREL/AWS continuous dataset represented as shaded contours and (b) eastern dataset represented as points with additional boxes representing subsets of data points

From the NREL Eastern Dataset, an annual wind speed trend was found for the three dataset years (2004, 2005, and 2006) with the resolution of hourly data. The hourly generation data are necessary for the AVERT analysis to quantify the accurate hourly emissions reduction. This annual wind speed trend was applied to the NREL/AWS continuous dataset to generate the annualized wind speed trend at all Lake Michigan locations. In this dataset integration, the generation (and emissions reduction) results are identical within the same NREL/AWS dataset wind speed regions. For the locations that straddle more than one wind speed region, the OWF results were interpolated.

To determine the total electricity generation at each location from the annual wind speed trend, first the wind profile power law is used to extrapolate the dataset height of 90m to the accurate hub height

of 100m (using an α of 0.11)¹ as shown in Eq. 1. The hub-height hourly wind speed data are then combined with the Vestas V112 3.0 MW wind turbine power curve in Figure A3 in Appendix A (Vestas Wind Systems A/S 2011). This is done at constant air density of 1.225 kg/m³ to determine the hourly generation for the three NREL Eastern Dataset years (2004, 2005, and 2006). The seasonal temperature variation and also the power curve cut-in and cut-out speed were also analyzed for their impact on generation and effects were found to be minimal. Details on this analysis can be found in Appendix A.

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{h_2}{h_1}\right)^\alpha \quad (1)$$

The total generation is then scaled from this calculation of one turbine into the study's OWF size of 100 turbines, assuming identical generation capabilities, with 17% losses (from wake effects, transmission losses, and turbine availability) (Chiang, et al. 2015) (NREL 2012). This calculation determined the hourly generation over the study period for the 300 MW OWF in the Michigan side of Lake Michigan.

2.2. Emission Quantification

EPA's AVERT (AVoided Emissions and geneRation Tool) was used to determine the temporal emissions reduction impacts resulting from the variable pattern of wind generation (U.S. EPA 2014). As mentioned previously, AVERT is a statistical model (as opposed to economic dispatch or market trading model) that analyzes plant capacity factors to determine the offset impacts in the entire grid region where the electricity generation reduction occurs. AVERT models renewable generation, in this case offshore wind generation, as a reduction in load. The load is categorized in bins and each generator is assigned a probability of running for each bin based on historical generation data. This model considers the interconnections and trading among power systems in different states since an OWF in Lake Michigan can potentially offset East Coast emissions based on AVERT (if they come from marginal power plants) (U.S. EPA 2014). However, AVERT does not model transmission constraints, ramping/cycling trend changes, or operation cost (U.S. EPA 2014). Despite these limitations, AVERT is the best publicly available choice for this study as other emission quantification methods, such as eGRID (Emissions & Generation Resource Integrated Database), do not consider the marginal plants or hourly variation (Ryan, Keoleian and Johnson 2016) (U.S. EPA 2014). AVERT is also insensitive to the actual physical location of the renewable energy technology within the AVERT region, so varying the OWF location

¹ This is the generally accepted value of wind power extrapolation over open water (Hsu, Meindl and Gilhousen 1994). However, in testing the wind shear value, varying it to 0.148 (upper range) would add about 0.4% to the wind speed, which is a negligible impact.

within the same wind speed region does not impact the emission results. AVERT results indicate the emissions reduction occur at plants throughout the region, not just at nearby locations (such as western Michigan).

The hourly generation in 2004, 2005, and 2006 were used as inputs for AVERT to determine the hourly emission impact. The AVERT analysis used the latest available electricity generation grid mix (from 2014) to estimate emissions reduction in the AVERT Great Lakes/Mid-Atlantic (EMW) generation region (see Appendix B Figure B1). In the sensitivity analysis, the AVERT Upper Mid-West (WMW) generation region was also analyzed for emissions reduction. AVERT reports hourly values for generation reduced (MWh) along with related reductions in CO₂ (tons), NO_x (lbs), and SO₂ (lbs), and respective annual emission rates (lbs/MWh). It also categorizes the emissions based on the respective power generation source (828 power plants within the EMW region) and location.

2.3. Benefits of Emissions Reduction

The valuation of emissions reduction was conducted in two separate scenarios: avoided damages and avoided abatement costs. It is important to note that the emission valuation represents a common metric, the benefits in dollars of avoided emissions, but the two scenarios embody two different approaches to valuation. It should also be noted that, at any given hour, the OWF may increase emissions due to higher-emission generators being elevated to the marginal plants as OWF generation increases, resulting in emission costs (rather than benefits) for that hour. However, in the total annual emission valuation, the benefits outweigh the costs.

In the first scenario (termed the base case scenario), damages were computed as the product of \$/unit (marginal damages) and number of units for CO₂, NO_x, and SO₂. The \$/unit figures are from the U.S. EPA SC-CO₂ (\$/lb CO₂) and Muller's APEEP model (\$/short ton NO_x and \$/short ton SO₂). The quantity units are from the AVERT emission results (short tons CO₂, lbs NO_x, and lbs SO₂). The APEEP results provide, at a county level, marginal damages by pollutant from a ground level source or point source (height < 250 meters, 250 – 500 meters, or > 500 meters) (N. Muller 2011). For this analysis, the NO_x and SO₂ pollutants were analyzed as a point source under 500 meters, representing the typical U.S. power generation stack height (Muller and Mendelsohn 2009). The locations for emission offsetting were extracted from AVERT to determine the counties impacted and the damages per unit mass of emissions reduction of those counties. Damages were weighted based on AVERT generation offset outputs to determine the emissions reduction benefits for 2004, 2005, and 2006.

The EPA social cost of carbon (SC-CO₂) of \$37.23/short ton at a 3% discount rate was used to value CO₂ damages (Interagency Working Group on Social Cost of Carbon May 2013, Revised July 2015). The SC-CO₂ increases over time as damages are estimated to increase in the future. The CO₂ benefits were analyzed for the 20 year period of 2015 to 2034, discounted by 3%, and reported in 2014 \$US. For the total 20 year lifespan of the OWF, the NO_x and SO₂ damage value were assumed to be constant each year and were discounted by 3% to determine the 2014 \$US net present value. The APEEP data are in 2007\$, so they were converted to 2014\$ with a factor of 1.14 (U.S. Bureau of Labor Statistics 2015). Other discount rates were not evaluated in this study but if the discount rate were to increase or decrease, the total emissions reduction benefits would decrease or increase respectively. This benefits calculation was completed separately for each of the three dataset years (2004 – 2006).

The second scenario, on market price emissions reduction benefits, is a cap-and-trade scenario with emission allowance prices to determine the avoided emission abatement costs. The idea here is that, while generation from an OWF will displace conventional generation, it will not reduce emissions of a pollutant capped by a regulatory program (Burtraw and Toman 1997) (Moore, Lewis and Cepela 2010). We apply the equilibrium condition for a cap-and-trade market of allowance price being equal to marginal cost of abatement. In this scenario, the emissions reduction benefit was computed using market prices for CO₂, NO_x, and SO₂ emission allowances. The CO₂ prices are from the Synapse 2015 CO₂ Price Forecast report (Luckow, et al. 2015). The NO_x and SO₂ prices are from U.S. EPA and U.S. EIA market allowance trading prices from two years, 2007 (Scenario 2a) and 2013 (Scenario 2b) (U.S. EPA 2015) (U.S. EIA 2012). Both years were analyzed since the EPA's Clean Air Interstate Rule (CAIR) for regulating NO_x and SO₂ emissions was deemed inadequate and dismissed in 2008; prices for NO_x and SO₂ plummeted thereafter. The prices for 2007 and 2013 thus represent two disparate outcomes, relatively high and relatively low prices (with 2013 similar to current prices) (U.S. EIA 2012). This scenario models prices based on existing and previously implemented cap-and-trade programs.

The same discounting and present value calculations from Scenario 1 were also performed in Scenario 2. The Synapse CO₂ analysis starts in 2020, but since the 20 year period of this study starts in 2015, the first 5 years were analyzed without any CO₂ emission reduction benefits. The NO_x and SO₂ benefits assume constant policy, which implies the emissions reduction benefits will be constant for the 20 year study period. The values in both scenarios are shown in Table 2 in the following section.

3. Results

The results are broken down into subsections on electricity generation, emission quantification, and benefits of emissions reduction. These results are separated based on the 2004, 2005, 2006 wind speed datasets and also the wind speed regions (minimum, maximum, and average). The 2004 average wind speed dataset was evaluated for temporal (monthly and hourly) trends and the 2004, 2005, and 2006 wind speed datasets were averaged together to analyze spatial (OWF siting location) trends.

3.1. Electricity Generation

To determine the electricity generation from the 300 MW offshore wind farm, the wind speed regions were analyzed as the average wind speed in the OWF location footprint. Wind speeds ranged from 7.0 m/s to 9.0 m/s with an average of 8.5 m/s. In addition to the total annual energy generation results, the generation in each hour was analyzed and determined to vary between years. The annual results from each dataset year can be averaged together since the annual generation results differed by 1.2% at most. The hourly results have large variations and should not be averaged together since this would change the shape of the annual generation trend and lead to different emissions reduction benefits. These values are summarized with the spatial results in Figure 3 (as capacity factors) and Figure B2 (Appendix B) as total annual generation (GWh/yr). The average capacity factor is found to be 44% which represents 1,154 GWh/year of generation from the 300 MW OWF. Capacity factor ranges from 32% to 47% and electricity generation ranges from 841 GWh/year to 1,237 GWh/year. Each location in Figure 3 represents a hypothetical wind farm.

Fig. 3: Capacity factor of 300 MW offshore wind farm in Lake Michigan

To evaluate hourly and monthly temporal trends, a heat map was generated through the summation of total generation across the months and hours with results for the 2004 wind speed dataset at average wind speed (8.5 m/s) shown in Figure 4. For the 2004 wind speed dataset, February had a lower wind speed compared to March and therefore lower electricity generation as seen in Figure 4. However, in the 2005 and 2006 datasets, the month of February has higher power generation than March due to higher wind speeds. Diurnal trends were also found in which the early morning hours have higher generation than day hours. For all three years, there is a distinct pattern found in the hourly and monthly trends. The trends in the original heat map are explored further to see how they affect emission quantification and emissions reductions benefits. In addition, a normalized heat map was generated by averaging the hourly values in each month. This resulted in similar trends to the original heat map. The highest generation was found to be in December (and other winter months) and the lowest was found to be in July (and other summer months).

Fig. 4: Heat map analysis of monthly and hourly trends of total annual electricity generation in MWh/hr (2004 dataset at average wind speed region)

3.2. Emission Quantification

AVERT reports hourly results in generation (MWh), CO₂ reduced (tons), NO_x reduced (lbs), and SO₂ reduced (lbs). The range of results (based on annual average wind speed region) is determined and shown in Table 1 (and Figure B3) for the annual emissions reduced. In using the signal-to-noise diagnostic as provided in AVERT, the R² value was found to range between 0.96 and 0.98, which indicated this was an appropriate use of the model for emission quantification.

Table 1. CO₂, NO_x, and SO₂ emissions reduction [tons/MW-yr or lbs/MW-yr] based on year and wind speed region for 300 MW OWF (see Appendix B Table B1 and Fig. B3 for complete table of wind speed regions and emissions reduced [tons or lbs reduced])

Wind Speed Region	tons/MW-yr CO ₂ reduced			lbs/MW-yr NO _x reduced			lbs/MW-yr SO ₂ reduced		
	2004	2005	2006	2004	2005	2006	2004	2005	2006
Lowest	2,198	2,183	2,234	4,099	4,036	4,163	10,229	10,086	10,470
Average	3,049	3,005	3,092	5,684	5,580	5,748	14,195	14,016	14,505
Highest	3,291	3,239	3,334	6,136	6,020	6,193	15,336	15,145	15,632

Between the 3 years, 2006 was found to have the largest emissions reduction benefits, however the variation is small (-2.05% to 1.77%). These annual emission quantification results are similar for each dataset year, and the results were averaged between the years to estimate annual emissions reduction benefits.

The emission rates from the AVERT model were also analyzed further to study the effects of a larger OWF. Since these emission rates do not use renewable energy generation in the calculation, the

emission rates are the same before and after the 300 MW OWF is introduced. The emission rates are: 0.875 tons CO₂/MWh; 1.565 lb NO_x/MWh; 3.863 lb SO₂/MWh. To evaluate the effect of larger wind farms, which may offset enough power plants to impact the emission rates, we analyzed a larger 30 GW OWF in the AVERT tool. This change in the AVERT model decreases the probability of units running. This resulted in the emission rates increasing by less than 1% for each pollutant. This slight increase is due to offsetting more natural gas peaking plants (low probability of running in lower load situations) that are generally cleaner than coal plants, so the new emission rates (grid emissions per fossil fuel generation) would come from predominantly dirtier power plants. However, the total system emission quantities would be decreasing.

The hourly and monthly electricity generation impact from AVERT shows similar emissions reduction results as predicted from the electricity generation model when analyzing each dataset year. The results from the 2004 average windspeed region for CO₂, NO_x, and SO₂ are shown in Figure 5. The quantities of CO₂, NO_x, and SO₂ emissions reduced follow similar monthly and hourly trends as the generation from Figure 4. The CO₂ emission reduction has a stronger correlation between high wind speeds and high emissions reduction while the NO_x and SO₂ emissions reduction have larger variations in the trends. While AVERT does have trends based on total hourly energy demand, which impacts the emissions reduction, the main factor leading to emissions reduction benefits is the amount of electricity generation offset. The significance of the wind speed trend is tested by modeling a constant hourly generation case (where the annual generation is equal to our original case) to determine the generation and corresponding emissions reduction. The constant hourly generation is not a flat offset because different plants may be offset, or certain plants would need to keep running depending on the demand. The impact of modeling the constant hourly generation was not substantial in causing certain hours or months to have larger emission offsets.

Fig. 5: Heat map analysis of total monthly and hourly (a) CO₂, (b) NO_x, and (c) SO₂ reduction at the 2004 average wind speed region [tons/year and lbs/year]

The emissions reduction were found to be focused on specific, geographically dispersed locations in the AVERT region, predominantly in Indiana, Pennsylvania, and Ohio. This is due to the AVERT model's statistical determination of the specific plants most likely to be offset. These locations are the same for any of the wind speed regions and dataset years with the only differences being the magnitude of emissions reduced. The spatial results for the 2004 average wind speed region can be found in Figure B4 (Appendix B). Identifying these locations is important in determining the NO_x and SO₂ valuation since they would change depending on the location of emissions reduction (and thus on the number of people affected).

3.3. Benefits of Emissions Reduction

The \$/input values of the emissions reduction benefits for Scenario 1 (base case) and Scenario 2 are presented in Table 2. Both scenarios were analyzed with the emission quantification results to accommodate differences in potential regulatory policies.

Table 2. Scenario 1 and Scenario 2 unit values. CO₂ prices are expressed in 20 year range; Scenario 2 NO_x and SO₂ prices are expressed in Scenario 2a valuation from 2007 then Scenario 2b valuation from 2013.

	units		
Scenario 1	CO ₂	37.2 – 52.7	2014\$/short ton
	NO _x	438.8	2014\$/short ton
	SO ₂	3,082	2014\$/short ton
Scenario 2	CO ₂	20 – 45.6	2014\$/short ton
	NO _x	884.7; 29.1	2014\$/short ton
	SO ₂	609.3; 1	2014\$/short ton

These input values are then applied to the AVERT emissions reduction quantities to determine the 20 year emissions reduction benefit of the OWF. The results in Figure 6 (and Table B2) show the separate CO₂, NO_x, SO₂, and total emissions reduction benefits for the 20 year period at each wind speed region. The benefits range from \$548 to \$807 million or \$1,827/kW to \$2,690/kW. The average wind speed region is at 8.5 m/s, so the average emissions reduction benefit in Lake Michigan is \$748 million or \$2,508/kW for this 300 MW OWF model.

Fig. 6: Scenario 1 present value emissions reduction benefits (CO₂, NO_x, SO₂, and total) of an OWF for 20 years with 3% discounting [2014 \$million] (See Appendix B Table B2 for the table of these results)

The spatial variation of the emissions reduction benefits in Scenario 1 are shown in Figure 7. Since the emissions reduction benefits result from the wind speed analysis, this figure has the same spatial trends as the generation in Figure B2 (Appendix B).

Fig. 7: Emissions reduction benefits from Scenario 1 results of an OWF [\$/kW]

These emissions reduction benefits can be understood as the share coming from the specific emission source or generation source, with CO₂ (and coal) dominating as the main factors in emissions reduction benefits. The CO₂ share of these benefits is found to be about 86% throughout the Lake region (followed by 12% from SO₂). Even though the unit values for CO₂ tend to be lower than those for NO_x and SO₂, significantly more CO₂ emissions are being reduced. The AVERT model indicated the majority of the annual emissions reduction of each pollutant (and also largest electricity reduction) comes from coal generation (Table 3). Looking at the generation reduced, coal represents 78.7% of the electricity being generated in this AVERT region (U.S. EPA 2014), but only about 70% of the electricity reduction. So this means there is more displacement of non-coal generation sources as opposed to an equal amount from each generation type with respect to OWF electricity generated. This makes sense as the OWF would be displacing peaking plants (typically marginal natural gas plants) which typically have cleaner emissions than coal plants.

Table 3. Electricity generation and emissions reduction by source (from AVERT)

	MWh	CO ₂	NO _x	SO ₂
coal %	70%	82.6%	88.3%	98.9%
NG %	27%	15.4%	8.1%	0.3%
oil/other %	3%	2.0%	3.7%	0.8%

As shown in Figure 8, the hourly emissions reduction benefits (2014\$/mill) vary by 23% between the highest emissions reduction hour to the lowest emissions reduction hour. For the monthly trends, the lowest emissions reduction month is 56% lower than the highest emissions reduction month. January, March, and December typically have the largest emissions reduction benefits while July and August have the smallest emissions reduction benefits, which is similar to the generation and emission quantification trends (Figure 8). Similarly, trends are still stronger across the month rather than the hour.

In analyzing the annual emissions reduction benefits (\$) per unit OWF electricity generated (MWh), the trends are very similar such that the benefits per generation are about 33 \$/MWh in almost all spatial and temporal cases (Figure 8). Depending on the hour or month, this can range from 27 \$/MWh to 39 \$/MWh. In comparison to the total benefits (\$), the pattern of the rate of emissions per generation (\$/MWh) are not identical. For example, December has the highest total benefits, but May has the highest rate of emissions per generation which represents a more efficient month for emission reduction benefits. This comes from reduction of the highest cost pollutant as dependent on the

generation mix and also the time of generation. Similarly, July has the lowest total benefits while January has the lowest rate of emissions per generation.

Fig. 8: Heat map analysis of total monthly and hourly emissions reduction benefits at the 2004 average wind speed region for a 300 MW OWF [2014\$mill and \$/MWh]

3.4. Scenario 2: Market Price Emissions Reduction Benefits

The final emissions reduction benefits (with the sensitivity of Scenario 2 included) are shown in Figure 9. One interesting note is the Scenario 2a NO_x emission value (from the 2007 market price) is actually higher than the Scenario 1 NO_x value. This is a case in which marginal abatement cost exceeds marginal damages under the NO_x pollution regulation. The results represent the range of benefits from the lowest wind speed region to the highest wind speed region and also the average benefit of the entire region (Figure 9). In Scenario 2a (2007), the benefits range from \$237.8 million to \$350.1 million with an average of \$326.5 million. In Scenario 2b (2013), the benefits range from \$215.8 million to \$317.6 million with an average of \$296.2 million. Figure 9 also shows the share of total emission reduction benefits contributed by CO₂ benefits. The emissions benefits per electricity generated is also determined for these scenarios: \$33/MWh (Scenario 1), \$14/MWh (Scenario 2a), and \$13/MWh (Scenario 2b). Scenario 2 is about 39% of the total benefits of Scenario 1, which is expected given that the current marginal abatement costs are lower than marginal damages. The difference in benefits from before and after CAIR (Scenario 2a and Scenario 2b) is relatively small in contrast to the magnitude of their difference with Scenario 1.

Fig. 9: Range (based on minimum and maximum wind speed regions) of emissions reduction benefits [2014 \$million] in Scenario 1 and 2a/b (with respective CO₂ reduction benefits share)

3.5. Sensitivity of NO_x and SO₂ Values by Location

The NO_x and SO₂ emission valuation can be further analyzed to understand how the location of emissions reduction can alter the magnitude of the benefits. Scenario 1 can be tested for three other cases by using the APEEP model with the various values shown in Table 4. The total U.S.-wide APEEP emissions reduction benefits would result in lower total emissions reduction benefits compared to Scenario 1 since the values of NO_x would be slightly higher (\$461/ton) but SO₂ would be much lower (\$1,890/ton). However, a Michigan-only analysis would have higher SO₂ values (\$2,176/ton) and lower NO_x values (\$428/ton), which in our OWF model would result in lower emissions reduction benefits compared to Scenario 1. Finally, averaging the entire AVERT 2014 Great Lakes/Mid-Atlantic (EMW) region together, regardless of the actual electricity generation reduction location, would result in higher NO_x and SO₂ values (\$511/ton and \$3,412/ton respectively) than Scenario 1. These comparisons demonstrate that this particular AVERT region would have larger emissions reduction benefits compared to other U.S. regions; but with respect to the region itself, the values of the emissions reduced from the actual plants are below the average values. The emissions reduction occurring in this region are therefore a result of low emitting marginal plants or areas of relatively low emission values.

Another sensitivity analysis considers trading in the electricity market in the Midcontinent Independent System Operator (MISO) region. In this sensitivity analysis, generation in Michigan would be traded with the western Midwest (WMW) states instead of the eastern Midwest (EMW) states that are modeled in AVERT. In changing the grid region, the values of NO_x and SO₂ changed to \$776/ton (82% increase) and \$1,926/ton (54% decrease), respectively (Table 4), while CO₂ remains the same (its value is not sensitive to emission reduction location). For the average wind speed region, the total emissions reduction benefits increased by only 3% (to \$773 million), but the particular benefits from NO_x and SO₂ had much larger differences. CO₂ benefits increased from \$645 million to \$718 million (due to higher reliance on coal leading to increased CO₂ reduction in this region), NO_x benefits increased from \$5.6 million to \$10 million, and SO₂ benefits decreased from \$98 million to \$45 million. This clearly illustrates that the emissions reduction benefits vary substantially depending on the location of the OWF generation. This emphasizes the importance of both determining the spatial locations of the emissions reduction values and accurately modeling where trading might occur in electricity markets.

Table 4: Scenario 1 locational sensitivity of NO_x and SO₂ benefit values

	Units	Scenario 1	all US	only MI	AVERT Great Lakes (avg)	AVERT Upper Mid-West
NO _x	2014\$/short ton	439	461	428	511	776
SO ₂	2014\$/short ton	3,082	1,890	2,176	3,412	1,926

4. Discussion

We integrated engineering calculations on wind resources with economic calculations on valuing emissions reduction in order to gain new insights into OWF siting in Lake Michigan. The calculated hourly generation shows the potential variation in emissions reduction benefits (between \$0/hour and \$19,334/hour), which depends on both the electricity generated during that hour and the type of generation displaced. Besides this temporal emissions reduction component, detailed economic calculations use this generation data to determine emissions reduction locations resulting from OWF siting locations. The analysis of both the temporal and spatial aspects of emissions reduction benefits creates new insight into variable renewable energy generation and its interaction with the electricity grid.

The emissions reduction benefits found in this study were also compared to the investment costs determined in related work (Chiang, et al. 2015). The emissions benefits were \$33/MWh overall in the entire Lake region, which would decrease the investment levelized cost of energy (\$249/MWh on

average) to \$216/MWh when analyzing system costs. In a scenario where an OWF is an emissions reduction strategy for the electrical grid, the emissions benefits were found to cost less than emission abatement technology, such as carbon capture and storage technology (Freund 2003) (Valentić, Žiković and Alfredo 2016). In the total valuation perspective, the total benefits including the emissions reduction (\$725 million on average) is about 49% of the investment cost (\$1,470 million on average) in the Lake Michigan region. The difference between the total valuation comparison and the cost per MWh comparison is due to the spatial variability of wind speed. The emissions reduction benefits are directly related to wind speed, but the investment cost is mainly driven by lake depth, which may not follow the wind speed patterns. Both these comparisons demonstrate the importance of estimating the emissions reduction benefits and carefully considering the environmental impacts of renewable energy projects.

The AVERT model has some important subtleties. First, the emissions reduction from AVERT do not always result in benefits. Occasionally the displaced marginal plant requires a higher emission plant to be utilized, in which case the emissions may increase. While this may occur in certain hours, the total overall emissions are reduced in all cases. Second, the emission location as determined in the AVERT model does not depend on the OWF location within a region. This is due to the limited ability for AVERT to reflect intra-regional transmission constraints. The emissions reduction and their related benefits may occur closer to the OWF if transmission constraints are binding. Finally, the current electricity generation impacts and emissions reduction were extrapolated for the 20 year time period, which does not account for an ever-changing electricity grid. Current energy demand is projected to increase and stronger government mandates will likely modify the existing electricity grid mix over this time period. This future grid was not evaluated or modeled in this study.

5. Conclusion

Renewable energy has the ability to reduce system-wide pollution emissions by offsetting fossil fuel generation sources. This is especially important as the regulations regarding allowable emissions in the U.S. continue to get stricter. Being able to quantify these emissions reduction benefits with respect to current, future, and potential emission policies is essential for understanding the social value of renewables and for educating decision makers about these values. This study shows how the emissions reduction can be quantified and valued in this region using publicly available data and models to demonstrate the additional benefits of an OWF in the Lake Michigan region.

We found that the spatial and temporal patterns of electricity generation drive the magnitude of emissions reduction benefits. The local marginal emissions factors for CO₂, SO₂, and NO_x vary throughout the day and seasonally. The largest benefits were found to be in the highest wind speed regions of Lake Michigan, which are in the middle of the Lake. This large region approximately corresponds with the region of high investment cost region, which are a function of distance from shore and water depth. The largest factor in the annual electricity generated, leading to emissions reduction benefits, was the high wind speed regions. For the annual temporal trends, the monthly generation trends were stronger than the hourly generation trends. The drivers of these emissions reduction benefits were mainly CO₂ emission reduction and coal plant emissions reduction.

While we believe that this analysis captures the most significant impacts, the environmental impact studied here only represents the emissions reduction benefits of the electricity generation phase. The emissions produced during the construction and installation of the OWF are not estimated or included. The magnitude of these impacts is relatively small (Tsai, et al. 2016), but future studies may wish to consider this for a more comprehensive analysis. Second, this study only analyzed the CO₂, NO_x, and SO₂ emission impacts and does not consider particulate matter, volatile organic compounds, mercury, or other pollutants. While this study shows that the reduction of CO₂ provides the largest benefits, it may be useful in future work to quantify and value all pollutants with respect to future policy considerations. Third, the differences between the annual NO_x and ozone NO_x damage costs were not analyzed separately since the total NO_x contribution to total emission damages was found to be minimal (compared to CO₂). The ozone season NO_x emissions (May 1st to September 30th) were found to be between 18% to 34% lower than the annual NO_x emissions, which is in accordance with the enforced policies on pollutants (U.S. EPA 2015). The policy determining the NO_x and SO₂ damage cost value is still important, but emissions reduction benefits from these pollutants are very small compared to CO₂ emission reduction benefits. So CO₂ damage cost value is a more influential factor in emissions benefits.

This study can contribute to policy development and stakeholder engagement by evaluating the emissions reduction benefits of OWFs. Using the approach from this paper, analysts can quantify the relative emissions reduction benefits across potential renewable energy and energy efficiency projects. Policy makers could emphasize subsidies, incentives, and mandates that encourage the development of projects based on optimal emissions reductions and their related economic benefits, as revealed by our method. With wind speed datasets and the AVERT and APEEP models, this work can be replicated for determining the emissions reduction benefits of an added wind farm in other locations in the U.S.

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6. Appendix A

Appendix A is used to further elaborate on the methods used for determining electricity generation in this study.

The electricity generation calculation combined two datasets in order to determine hourly, spatial wind speeds. One dataset was the NREL/AWS continuous annual average wind speed dataset, with 20 wind speed regions at a 90m hub height (NREL 2012). The second dataset was the NREL Eastern Wind Speed dataset, which had 10 minute interval wind speed data for three years (2004, 2005, and 2006) at 80m. This NREL Michigan Eastern Dataset contains 147 spatially distributed data points in the Michigan region of Lake Michigan, all in the northern area of the lake (NREL 2012). There are also 51 data points in the Indiana region and 51 data points in the Illinois region of Lake Michigan, all in the southwestern area of the lake (NREL 2012). This is illustrated in Figure 2.

The NREL Michigan Eastern Dataset is first averaged into an hourly speed from the 10 minute resolution data. This is necessary to generate hourly generation data to determine hourly emissions using AVERT. Next, all the datapoints are individually normalized, based on annual average wind speed, into percent deviations from the average wind speed of the datapoint location. This allows the data to be combined to generate an annual wind speed trend for the 2004, 2005, and 2006 dataset years which is applicable to all Lake locations. To verify the aggregation of the set of data points, the west side data points of the Lake were compared to the east side data points of the Lake in a monthly diurnal heat map (Figure A1). The north side data points were also compared to the south side data points. The values in Figure A1 represent the power in the wind normalized by the annual average power in the wind for two locations in the north, south, west, and east regions. The gradient colors represent the monthly trends of low and high generation. The maps show relatively strong correlations across time-of-day by month for these locations. This monthly consistency between the different regions of the Lake indicate that it is appropriate for the data to be combined for average wind speed trend analysis. Since the south side data points were not part of the Michigan region of Lake Michigan, they were excluded, but this comparison justifies the extrapolation of the annual wind speed trend of the northern Michigan data points throughout the entire Lake region. The datapoints analyzed on the north, south, west, and east sides are annotated in Figure 2. From this, the annual wind speed trends are determined using the north side points for 2004, 2005, and 2006, and these can be applied to the NREL/AWS dataset.

West Side Data Points (#347, 348)																									
	Month												Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	1.04	0.85	1.08	1.28	1.31	1.21	0.98	0.90	1.18	1.13	1.18	1.12	0	1.02	0.85	1.09	1.30	1.32	1.22	1.00	0.89	1.18	1.13	1.19	1.10
1	1.10	0.84	1.14	1.29	1.34	1.19	0.90	0.85	1.16	1.15	1.17	1.09	1	1.08	0.85	1.15	1.30	1.35	1.21	0.90	0.85	1.16	1.15	1.18	1.07
2	1.16	0.96	1.18	1.18	1.39	1.23	0.82	0.80	1.22	1.27	1.23	1.20	2	1.15	0.97	1.19	1.18	1.40	1.24	0.82	0.81	1.21	1.26	1.23	1.18
3	1.16	1.06	1.18	1.20	1.33	1.19	0.79	0.77	1.19	1.32	1.27	1.29	3	1.13	1.07	1.19	1.20	1.35	1.18	0.78	0.77	1.17	1.32	1.26	1.28
4	1.15	1.08	1.09	1.30	1.25	1.20	0.83	0.78	1.11	1.40	1.33	1.33	4	1.13	1.08	1.09	1.28	1.26	1.21	0.81	0.78	1.10	1.39	1.33	1.31
5	1.13	1.03	1.11	1.25	1.19	1.07	0.82	0.74	1.07	1.36	1.33	1.23	5	1.11	1.03	1.12	1.25	1.21	1.08	0.82	0.74	1.06	1.36	1.32	1.22
6	1.10	1.00	1.11	1.23	1.14	1.00	0.70	0.66	1.01	1.35	1.31	1.20	6	1.08	1.00	1.12	1.23	1.15	1.00	0.70	0.65	1.01	1.35	1.31	1.20
7	1.03	0.99	1.07	1.26	1.08	0.91	0.68	0.59	0.96	1.29	1.18	1.19	7	1.01	0.99	1.07	1.27	1.09	0.91	0.68	0.60	0.96	1.29	1.17	1.18
8	0.94	0.96	1.06	1.21	1.08	0.91	0.68	0.56	0.91	1.20	1.15	1.16	8	0.92	0.97	1.06	1.23	1.08	0.91	0.68	0.56	0.91	1.20	1.13	1.15
9	0.93	0.94	0.97	1.16	1.11	0.81	0.66	0.54	0.86	1.10	1.17	1.18	9	0.92	0.94	0.97	1.16	1.10	0.82	0.65	0.54	0.86	1.10	1.16	1.16
10	0.92	0.92	0.94	1.13	1.14	0.80	0.61	0.55	0.83	1.06	1.14	1.19	10	0.91	0.92	0.94	1.13	1.14	0.80	0.60	0.55	0.82	1.07	1.13	1.19
11	0.91	0.88	0.97	1.12	1.17	0.81	0.59	0.53	0.85	1.10	1.16	1.19	11	0.90	0.88	0.98	1.11	1.17	0.81	0.59	0.53	0.84	1.09	1.15	1.19
12	0.79	0.75	0.80	0.93	0.97	0.60	0.48	0.42	0.70	0.89	1.08	1.00	12	0.78	0.75	0.80	0.93	0.97	0.60	0.48	0.42	0.69	0.88	1.07	1.00
13	0.82	0.75	0.80	0.82	0.88	0.56	0.44	0.39	0.68	0.90	1.13	0.99	13	0.80	0.75	0.80	0.82	0.89	0.57	0.44	0.38	0.68	0.89	1.12	0.99
14	0.96	0.94	0.90	0.80	0.97	0.63	0.49	0.43	0.75	1.04	1.23	1.12	14	0.94	0.93	0.90	0.80	0.99	0.64	0.50	0.42	0.76	1.03	1.22	1.11
15	1.00	0.98	0.92	0.76	0.99	0.68	0.54	0.46	0.76	1.00	1.21	1.21	15	0.99	0.99	0.93	0.76	1.01	0.70	0.55	0.45	0.76	0.99	1.22	1.18
16	0.98	0.87	0.86	0.80	0.99	0.86	0.68	0.48	0.79	1.03	1.13	1.20	16	0.96	0.88	0.89	0.81	1.01	0.86	0.68	0.49	0.79	1.02	1.14	1.16
17	0.90	0.75	0.80	0.81	1.02	1.00	0.80	0.55	0.84	0.97	1.03	1.15	17	0.88	0.77	0.83	0.82	1.04	1.00	0.79	0.56	0.82	0.96	1.03	1.13
18	0.89	0.67	0.83	0.84	1.19	1.13	0.89	0.72	1.01	0.96	1.04	1.06	18	0.85	0.68	0.85	0.85	1.22	1.15	0.89	0.72	0.99	0.96	1.03	1.05
19	0.87	0.66	0.82	0.91	1.31	1.26	1.01	0.82	1.13	0.98	1.04	1.02	19	0.85	0.66	0.84	0.91	1.33	1.30	1.03	0.84	1.11	0.98	1.03	1.01
20	0.86	0.70	0.92	0.94	1.30	1.39	1.14	0.81	1.15	1.08	1.03	1.00	20	0.84	0.70	0.92	0.96	1.32	1.41	1.15	0.84	1.17	1.08	1.03	1.00
21	0.86	0.76	0.99	1.03	1.38	1.43	1.03	0.89	1.22	1.15	1.08	1.04	21	0.85	0.77	1.00	1.06	1.40	1.42	1.05	0.89	1.22	1.16	1.08	1.02
22	0.92	0.83	1.06	1.13	1.35	1.45	1.08	0.88	1.31	1.18	1.15	1.08	22	0.91	0.83	1.09	1.16	1.38	1.44	1.10	0.89	1.30	1.18	1.15	1.06
23	1.02	0.90	1.11	1.22	1.37	1.40	1.03	0.89	1.32	1.16	1.24	1.19	23	1.00	0.90	1.13	1.24	1.39	1.40	1.06	0.90	1.32	1.16	1.23	1.18
East Side Data Points (#462, 465)																									
	Month												Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	1.09	1.05	0.93	1.09	0.81	0.83	0.78	0.62	0.75	1.04	1.21	1.31	0	1.08	1.05	0.93	1.10	0.84	0.81	0.77	0.63	0.76	1.05	1.22	1.30
1	1.06	1.05	0.98	1.19	0.76	0.72	0.71	0.57	0.69	1.06	1.22	1.27	1	1.05	1.05	0.97	1.18	0.77	0.71	0.72	0.56	0.70	1.07	1.22	1.27
2	1.12	1.14	1.01	1.17	0.78	0.76	0.62	0.55	0.77	1.03	1.28	1.29	2	1.11	1.14	1.01	1.15	0.77	0.76	0.62	0.54	0.79	1.03	1.28	1.30
3	1.22	1.20	1.17	1.13	0.87	0.91	0.62	0.65	0.80	1.10	1.36	1.37	3	1.22	1.21	1.18	1.10	0.86	0.89	0.64	0.65	0.81	1.11	1.37	1.38
4	1.28	1.16	1.28	1.15	0.79	0.92	0.58	0.67	0.89	1.23	1.36	1.50	4	1.28	1.16	1.27	1.13	0.78	0.92	0.59	0.67	0.88	1.25	1.38	1.52
5	1.25	1.10	1.26	1.08	0.83	0.88	0.56	0.66	0.87	1.29	1.38	1.42	5	1.26	1.09	1.26	1.05	0.83	0.87	0.55	0.66	0.87	1.31	1.39	1.43
6	1.25	1.08	1.19	0.99	0.85	0.82	0.54	0.63	0.87	1.29	1.40	1.42	6	1.24	1.08	1.18	0.98	0.84	0.82	0.54	0.64	0.87	1.32	1.41	1.41
7	1.27	1.03	1.20	1.01	0.82	0.84	0.57	0.69	0.87	1.39	1.45	1.40	7	1.28	1.04	1.20	1.00	0.82	0.84	0.56	0.70	0.87	1.39	1.45	1.40
8	1.22	1.02	1.12	1.09	0.81	0.87	0.57	0.68	0.85	1.42	1.46	1.33	8	1.22	1.02	1.13	1.07	0.80	0.86	0.56	0.68	0.84	1.42	1.45	1.33
9	1.21	1.02	1.09	1.16	0.89	0.85	0.56	0.64	0.84	1.31	1.44	1.32	9	1.22	1.03	1.09	1.15	0.89	0.83	0.55	0.64	0.84	1.32	1.43	1.32
10	1.18	1.04	1.07	1.24	0.89	0.85	0.58	0.59	0.81	1.25	1.33	1.38	10	1.18	1.05	1.08	1.23	0.89	0.84	0.57	0.59	0.81	1.25	1.32	1.39
11	1.16	1.04	1.00	1.26	0.99	0.81	0.60	0.58	0.84	1.22	1.28	1.45	11	1.17	1.04	1.01	1.26	0.98	0.80	0.60	0.58	0.84	1.24	1.27	1.45
12	1.03	0.92	0.80	1.06	0.89	0.68	0.48	0.44	0.66	1.04	1.27	1.32	12	1.04	0.93	0.80	1.05	0.88	0.68	0.48	0.44	0.66	1.04	1.26	1.33
13	1.02	0.90	0.75	0.96	0.84	0.70	0.50	0.44	0.61	0.99	1.27	1.28	13	1.02	0.91	0.74	0.98	0.83	0.69	0.50	0.44	0.61	1.01	1.26	1.28
14	1.11	1.02	0.78	0.87	0.90	0.78	0.54	0.49	0.71	1.14	1.34	1.43	14	1.11	1.02	0.77	0.86	0.91	0.77	0.54	0.49	0.71	1.16	1.34	1.43
15	1.20	1.07	0.79	0.83	0.93	0.77	0.65	0.55	0.81	1.22	1.48	1.48	15	1.20	1.08	0.79	0.81	0.95	0.76	0.64	0.55	0.80	1.23	1.49	1.47
16	1.17	1.08	0.83	0.80	1.02	0.84	0.79	0.56	0.86	1.25	1.49	1.48	16	1.17	1.09	0.84	0.79	1.03	0.83	0.79	0.56	0.85	1.26	1.52	1.48
17	1.18	1.09	0.82	0.76	0.89	0.85	0.80	0.61	0.85	1.24	1.39	1.57	17	1.16	1.09	0.84	0.75	0.89	0.81	0.81	0.60	0.83	1.24	1.41	1.57
18	1.16	1.09	0.79	0.78	0.92	1.12	0.88	0.63	0.88	1.25	1.29	1.54	18	1.16	1.10	0.79	0.78	0.94	1.08	0.89	0.63	0.86	1.26	1.33	1.55
19	1.12	1.06	0.83	0.76	0.97	1.15	0.96	0.69	0.90	1.21	1.24	1.48	19	1.13	1.07	0.82	0.78	0.99	1.11	0.97	0.68	0.89	1.21	1.28	1.49
20	1.07	1.05	0.84	0.75	0.91	1.21	1.04	0.70	0.85	1.17	1.21	1.51	20	1.07	1.06	0.83	0.76	0.92	1.18	1.03	0.70	0.85	1.18	1.26	1.51
21	1.04	1.04	0.91	0.81	0.93	1.13	1.00	0.66	0.89	1.15	1.30	1.48	21	1.04	1.04	0.90	0.82	0.94	1.09	0.99	0.65	0.87	1.14	1.31	1.49
22	1.06	1.00	0.95	0.82	0.88	1.14	0.88	<																	

North Side Data Points (#189, 190)																									
Hour	Month												Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
0	1.14	1.01	0.96	1.30	1.10	0.74	0.62	0.64	0.84	1.07	1.18	1.21	0	1.15	1.02	0.95	1.28	1.09	0.71	0.63	0.64	0.83	1.06	1.20	1.22
1	1.22	1.02	0.95	1.29	1.03	0.77	0.57	0.64	0.80	0.98	1.15	1.17	1	1.22	1.03	0.95	1.28	1.02	0.74	0.58	0.62	0.79	0.98	1.17	1.18
2	1.29	1.08	0.99	1.26	0.91	0.83	0.58	0.68	0.85	1.06	1.21	1.25	2	1.31	1.09	0.98	1.25	0.92	0.80	0.58	0.68	0.84	1.06	1.23	1.27
3	1.34	1.08	1.05	1.15	0.83	0.84	0.64	0.72	0.88	1.13	1.21	1.33	3	1.35	1.10	1.05	1.14	0.82	0.84	0.63	0.71	0.86	1.12	1.22	1.35
4	1.27	1.07	0.96	1.13	0.78	0.91	0.63	0.71	0.89	1.20	1.29	1.36	4	1.28	1.08	0.98	1.12	0.76	0.90	0.62	0.71	0.87	1.18	1.31	1.37
5	1.29	1.10	1.03	1.19	0.72	1.06	0.59	0.76	0.97	1.30	1.41	1.40	5	1.27	1.12	1.03	1.16	0.72	1.03	0.58	0.75	0.98	1.32	1.42	1.40
6	1.23	1.08	1.11	1.19	0.74	0.90	0.57	0.74	1.01	1.35	1.41	1.41	6	1.24	1.10	1.12	1.20	0.73	0.89	0.55	0.74	1.02	1.34	1.44	1.42
7	1.20	0.98	1.09	1.17	0.84	0.91	0.62	0.71	0.95	1.34	1.42	1.34	7	1.20	1.00	1.10	1.16	0.84	0.91	0.61	0.71	0.95	1.34	1.43	1.34
8	1.19	0.96	1.08	1.13	0.92	0.98	0.69	0.71	0.90	1.28	1.47	1.30	8	1.20	0.97	1.09	1.13	0.92	0.98	0.69	0.72	0.89	1.29	1.47	1.31
9	1.20	1.00	1.08	1.14	0.94	0.95	0.66	0.69	0.88	1.16	1.45	1.31	9	1.20	1.00	1.09	1.14	0.95	0.95	0.65	0.70	0.87	1.14	1.45	1.31
10	1.22	1.05	0.99	1.14	1.01	0.86	0.63	0.61	0.90	1.18	1.40	1.35	10	1.22	1.06	1.01	1.16	1.01	0.87	0.62	0.61	0.90	1.17	1.40	1.36
11	1.15	1.01	0.91	1.19	1.12	0.88	0.62	0.60	0.89	1.21	1.38	1.42	11	1.16	1.02	0.91	1.20	1.13	0.88	0.60	0.60	0.89	1.21	1.38	1.44
12	0.96	0.89	0.76	1.02	0.92	0.70	0.49	0.48	0.67	0.97	1.34	1.27	12	0.96	0.88	0.76	1.03	0.93	0.69	0.47	0.47	0.66	0.98	1.33	1.28
13	1.03	0.89	0.78	0.93	0.84	0.66	0.42	0.42	0.61	0.97	1.29	1.22	13	1.03	0.90	0.78	0.94	0.83	0.67	0.41	0.42	0.61	0.97	1.31	1.24
14	1.17	1.00	0.82	0.90	0.91	0.69	0.47	0.46	0.70	1.06	1.31	1.33	14	1.18	1.01	0.83	0.91	0.89	0.70	0.46	0.45	0.69	1.07	1.32	1.34
15	1.26	1.05	0.85	0.77	0.97	0.75	0.53	0.52	0.76	1.10	1.36	1.46	15	1.27	1.07	0.85	0.78	0.95	0.74	0.53	0.51	0.75	1.11	1.39	1.48
16	1.27	1.08	0.88	0.71	1.13	0.88	0.66	0.60	0.84	1.06	1.35	1.47	16	1.28	1.08	0.87	0.72	1.12	0.85	0.65	0.59	0.84	1.07	1.36	1.50
17	1.23	1.03	0.92	0.74	1.15	0.94	0.70	0.66	0.85	1.08	1.29	1.44	17	1.23	1.04	0.92	0.75	1.14	0.93	0.69	0.65	0.86	1.09	1.30	1.46
18	1.19	0.95	0.96	0.80	1.14	0.97	0.78	0.70	0.89	1.12	1.23	1.38	18	1.19	0.98	0.96	0.81	1.12	0.94	0.76	0.69	0.88	1.12	1.24	1.40
19	1.10	0.95	0.96	0.86	1.19	0.98	0.80	0.76	0.91	1.15	1.17	1.31	19	1.10	0.96	0.95	0.85	1.17	0.97	0.79	0.75	0.90	1.14	1.18	1.33
20	1.02	0.96	0.97	0.92	1.21	0.93	0.79	0.78	0.89	1.22	1.08	1.29	20	1.02	0.97	0.96	0.91	1.21	0.90	0.78	0.77	0.88	1.21	1.09	1.31
21	1.02	0.98	1.01	1.04	1.23	0.97	0.85	0.75	0.92	1.22	1.05	1.30	21	1.01	1.00	0.99	1.03	1.23	0.93	0.85	0.72	0.90	1.21	1.05	1.31
22	1.03	1.01	0.98	1.12	1.22	0.86	0.87	0.71	0.98	1.19	1.12	1.32	22	1.03	1.02	0.97	1.10	1.21	0.85	0.87	0.70	0.97	1.18	1.13	1.34
23	1.09	1.06	1.03	1.27	1.17	0.85	0.75	0.69	1.02	1.16	1.21	1.34	23	1.10	1.07	1.02	1.25	1.17	0.83	0.75	0.68	1.00	1.15	1.22	1.35
South Side Data Points (#2824, #2879)																									
Hour	Month												Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
0	1.35	0.81	1.25	1.61	0.92	0.69	0.74	0.69	0.79	1.11	1.29	1.25	0	1.35	0.81	1.26	1.63	0.94	0.68	0.74	0.68	0.78	1.10	1.29	1.26
1	1.38	0.84	1.24	1.57	0.96	0.77	0.83	0.79	0.72	1.16	1.35	1.27	1	1.38	0.84	1.24	1.57	0.97	0.75	0.78	0.79	0.71	1.15	1.35	1.27
2	1.47	1.02	1.21	1.61	0.93	0.76	0.63	0.66	0.70	1.15	1.51	1.37	2	1.47	1.02	1.21	1.62	0.92	0.74	0.62	0.66	0.70	1.15	1.52	1.37
3	1.55	1.11	1.39	1.69	0.99	0.78	0.68	0.62	0.79	1.23	1.63	1.50	3	1.55	1.11	1.39	1.71	0.99	0.76	0.68	0.62	0.79	1.24	1.63	1.51
4	1.56	1.16	1.47	1.82	1.04	0.85	0.66	0.59	0.87	1.30	1.62	1.56	4	1.56	1.16	1.46	1.82	1.05	0.85	0.66	0.60	0.86	1.30	1.63	1.57
5	1.49	1.15	1.41	1.76	1.04	0.79	0.66	0.58	0.78	1.23	1.67	1.48	5	1.50	1.15	1.41	1.76	1.04	0.79	0.66	0.58	0.79	1.23	1.68	1.49
6	1.41	1.10	1.41	1.89	1.11	0.72	0.66	0.65	0.74	1.29	1.62	1.43	6	1.40	1.09	1.42	1.88	1.11	0.72	0.66	0.65	0.73	1.25	1.62	1.43
7	1.37	1.05	1.47	1.80	1.13	0.72	0.67	0.60	0.72	1.17	1.56	1.42	7	1.38	1.05	1.47	1.81	1.13	0.72	0.67	0.60	0.71	1.17	1.56	1.43
8	1.31	1.01	1.43	1.75	1.17	0.62	0.60	0.58	0.72	1.12	1.49	1.43	8	1.32	1.01	1.44	1.75	1.17	0.62	0.60	0.57	0.72	1.13	1.50	1.44
9	1.24	1.03	1.41	1.65	1.16	0.57	0.55	0.52	0.66	1.11	1.48	1.42	9	1.24	1.03	1.42	1.65	1.17	0.57	0.55	0.52	0.67	1.11	1.48	1.42
10	1.15	1.03	1.41	1.55	1.02	0.56	0.51	0.55	0.65	1.03	1.45	1.40	10	1.15	1.03	1.41	1.54	1.02	0.55	0.51	0.55	0.65	1.03	1.46	1.40
11	1.07	0.97	1.32	1.47	1.03	0.52	0.49	0.46	0.67	1.01	1.42	1.37	11	1.07	0.97	1.33	1.47	1.01	0.52	0.49	0.46	0.67	1.01	1.43	1.37
12	1.01	0.81	1.14	1.46	0.94	0.43	0.40	0.38	0.58	0.90	1.24	1.33	12	1.01	0.81	1.14	1.47	0.94	0.42	0.40	0.38	0.58	0.90	1.24	1.33
13	1.00	0.71	1.07	1.49	0.91	0.40	0.38	0.37	0.52	0.89	1.19	1.41	13	1.00	0.71	1.07	1.50	0.91	0.39	0.38	0.37	0.53	0.90	1.20	1.41
14	1.01	0.77	1.04	1.43	0.84	0.44	0.46	0.37	0.51	0.93	1.28	1.55	14	1.01	0.77	1.04	1.43	0.83	0.43	0.46	0.36	0.52	0.94	1.29	1.55
15	1.12	0.80	1.07	1.28	0.77	0.44	0.40	0.36	0.54	0.93	1.30	1.71	15	1.12	0.79	1.07	1.27	0.75	0.44	0.39	0.35	0.54	0.93	1.30	1.71
16	1.12	0.75	1.11	1.14	0.75	0.44	0.35	0.47	0.51	0.85	1.30	1.61	16	1.12	0.75	1.11	1.14	0.74	0.44	0.35	0.42	0.50	0.85	1.30	1.61
17	1.09	0.69	1.11	1.08	0.72	0.53	0.47	0.36	0.48	0.82	1.17	1.39	17	1.09	0.69	1.11	1.07	0.71	0.53	0.45	0.35	0.48	0.81	1.17	1.39
18	1.07	0.64	1.14	1.14	0.74	0.61	0.52	0.38	0.49	0.80	1.07	1.28	18	1.06	0.64	1.14	1.14	0.74	0.62	0.51	0.38	0.50	0.80	1.08	1.28
19	1.10	0.67	1.22	1.26	0.75	0.63	0.58	0.46	0.52	0.87	1.03	1.17	19	1.10	0.68	1.21	1.26	0.75	0.64	0.61	0.47	0.53	0.87	1.04	1.16
20	1.15	0.68	1.25	1.41	0.83	0.78	0.64	0.50	0.59	0.91	1.05	1.11	20	1.15	0.68	1.25	1.41	0.83	0.79	0.65	0.50	0.59	0.91	1.05	

Power curve V112-3.0 MW

Fig. A3: Power curve of Vestas V112 3.0 MW turbine (Vestas Wind Systems A/S 2011)

To incorporate the seasonal temperature variation on generation, different air density values were evaluated. At higher temperatures (summer months) the air density would decrease (for example, 1.2 kg/m^3) and at lower temperatures (winter months) the air density would increase (1.25 kg/m^3). These air densities have different power curves (Vestas Wind Systems A/S 2011), but the change in annual generation is -1.7% and 1.2% respectively for the lower and higher air densities (higher and lower temperature). This shows that there will be higher generation in the winter months compared to the summer months at the same wind speeds, but the differences are minimal overall.

The power curve calculation also takes into account the cut-in speed at 3 m/s and cut-out speed at 25 m/s. To assess the impacts of a hysteresis loop, we tested a re-cut in speed of 23 m/s, which was found to have at most 0.15% variation on the total generation; its effect was not included in this analysis.

7. Appendix B

Appendix B contains several additional figures and tables that can provide additional information for the study.

Fig. B1: US EPA's AVERT modeling 10 different electricity regions

Fig. B2: Electricity generation [GWh/year] in Lake Michigan from 300 MW offshore wind farm

Table B1: Full table representing the CO₂, NO_x and SO₂ emissions reduction based on year and wind speed region/location

Extrapolated wind speed	tons CO ₂ reduced			lbs NO _x reduced			lbs SO ₂ reduced		
	2004	2005	2006	2004	2005	2006	2004	2005	2006
7.0	659,300	655,000	670,300	1,229,600	1,210,800	1,248,800	3,068,700	3,025,800	3,140,900
7.2	704,900	699,700	716,800	1,314,400	1,294,800	1,335,000	3,280,300	3,238,300	3,360,300
7.5	749,500	743,300	762,100	1,397,400	1,376,500	1,418,800	3,487,200	3,446,200	3,574,300
7.7	792,900	785,400	806,000	1,478,200	1,455,600	1,499,900	3,689,000	3,647,300	3,781,100
8.0	835,000	825,800	848,200	1,556,600	1,531,600	1,578,000	3,885,300	3,840,900	3,979,700
8.2	875,600	864,400	888,900	1,632,300	1,604,200	1,653,000	4,075,300	4,026,400	4,170,100
8.5	914,700	901,600	927,600	1,705,200	1,673,900	1,724,500	4,258,600	4,204,900	4,351,600
8.7	952,100	937,000	964,600	1,775,000	1,740,800	1,792,600	4,434,700	4,376,600	4,524,100
9.0	987,300	971,600	1,000,100	1,840,900	1,806,100	1,858,000	4,600,800	4,543,400	4,689,500

Fig. B3: CO₂, NO_x, and SO₂ emissions reductions based on 2004 dataset year and wind speed region/location (See Table 1 and Table B1 for complete table of wind speed regions and emissions reduced in emissions/MW and total emissions)

Fig. B4: AVERT CO₂ emissions reduction locations based on 2004 average wind speed region

Table B2: Scenario 1 present value emissions reduction benefits (CO₂, NO_x, SO₂, and total) of an OWF for 20 years with 3% discounting [2014 \$million] (see Fig. 6 for graphical results)

Wind Speed Region		CO ₂ avg	NO _x avg	SO ₂ avg	Total Emissions Reduction Benefits
m/s		2014\$mill	2014\$mill	2014\$mill	2014\$mill
min	7.0	466.2	4.0	70.6	548
	7.2	498.3	4.3	75.5	578
	7.5	529.7	4.6	80.3	615
	7.7	560.1	4.8	85.0	650
	8.0	589.4	5.1	89.5	684
	8.2	617.6	5.3	93.8	717
avg	8.5	644.6	5.6	97.9	748
	8.7	670.4	5.8	101.9	778
max	9.0	695.1	6.0	105.7	807