Wind Power and Air Quality

REDUCING AIR POLLUTION AND CARBON EMISSIONS IN MICHIGAN

WEST MICHIGAN WIND ASSESSMENT | ISSUE BRIEF 7

The West Michigan Wind Assessment is a Michigan Sea Grant-funded project analyzing the benefits and challenges of developing utility-scale wind energy in coastal West Michigan.

More information about the project, including a wind energy glossary can be found at the website, www.gvsu.edu/wind.

Introduction

Wind turbines generate electricity without directly emitting air pollutants that are known to affect the climate and human health. Wind turbines, however, do not operate in a vacuum. They are integrated into the larger electrical grid that includes coal and nuclear plants, natural gas turbines, hydroelectric dams, solar panels and other technologies. The interactions between these electricity sources are complex. If a new wind farm "displaces" a more polluting energy source - for example if the wind farm allows a coal-fired power plant to slow down or close - the wind farm could reduce air pollution significantly. Accordingly, the pollution-reduction benefits from wind turbines depend on which, if any, fuels they displace. Now that utility-scale wind farms have been in operation around the world for more than two decades, it is possible to evaluate whether wind farms actually reduce air pollution from the electricity sector.

The benefits from wind turbines depend on which, if any, fuels they displace.

This issue brief summarizes the best available science on the air quality benefits of wind energy as it is integrated into the electric grid. The brief includes estimates of the pollution-reducing potential of wind energy in Michigan using a variety of methods and the results of several life-cycle, or cradle-to-grave, analyses for wind turbines. The science suggests that wind energy can be successfully integrated into the electricity grid and doing so can reduce emissions of air pollutants like sulfur dioxide (SO_2), nitrogen oxides (NO_x) and carbon dioxide (CO_2).

Estimates of how much wind farms reduce pollution, as well as the cost of those reductions, varies widely.

How Will Wind Energy Affect Air Pollution?

Wind turbines reduce air pollution by displacing a more polluting form of electricity generation with wind-generated energy. The more polluting the displaced fuel is, the more the environment benefits from the generated wind energy. Energy system modelers use a combination of historical electricity and pollution emissions data, computer models of grid interactions, and projections for future installations to estimate the air pollution emissions from different mixes of electricity generation sources. This technique is called dispatch modeling.

The project team reviewed 12 reports from the peer-reviewed, scientific literature and government agencies related to dispatch modeling and the integration of wind energy into the electricity grid. Estimates of how much wind farms reduce pollution, as well as the cost of those reductions, varies widely. These reductions are dependent on the electricity generation mix in a region. This mix depends on the location of the current energy source and which types of energy sources would be reduced if wind farms were built at that location. This section summarizes a recent report from the Department of Energy (DOE) *20% Wind Energy by 2030* and 12 other scientific papers on the air-pollution-reducing potential of wind energy (Table 1).

The Department of Energy predicts that if 20% of our electricity came from wind, we would reduce our natural gas consumption by about 50% and coal consumption by about 18%.

This would cost us an additional $40 billion above and beyond the $2 trillion investment in the electric grid that is needed to meet our growing energy needs.

As the title suggests, the report explores the costs and benefits of producing 20 percent of the country's electricity using wind energy by 2030. This wind scenario would require new wind farms be built with a total capacity of 293 GW, but that would offset the need for more coal-fired power plants and avoid the construction of 80GW of new coal capacity [1]. Wind energy could reduce our reliance on coal, but it would likely have a bigger effect on our use of natural gas. The Department of Energy predicts that if 20 percent of our electricity came from wind, we would reduce our natural gas consumption by about 50 percent and coal consumption by about 18 percent. Cumulative avoided CO_2 emissions would reach 7.6 billion tons by 2030 and 15 billion tons by 2050. This would keep carbon dioxide emissions from the electricity sector from increasing substantially over the next 25 years (Figure 1).

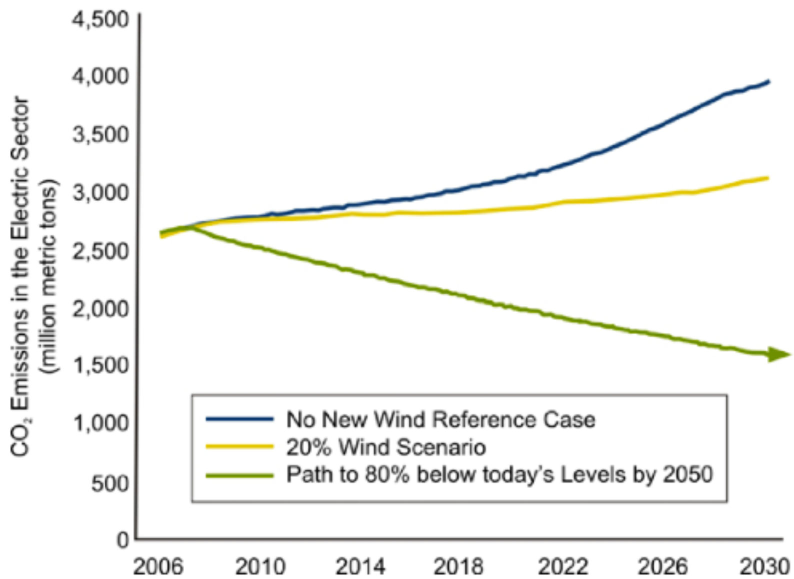


Figure 1: Generating 20% of the nation's electricity from wind can reduce CO_2 emissions from the electricity sector. Source: U.S. Dept. of Energy [1].

Government researchers estimate that we will need to spend $2 trillion on upgrading the U.S. electric gird over the next 30 years to meet the country's growing energy needs, regardless of the future mix of energy generation. If we build enough wind farms to generate 20 percent of our electricity from wind, we will need to invest an additional 2 percent ($40 billion) into improving the grid to accommodate this amount of wind energy [1]. This additional 2 percent investment in the grid would allow us to use a wide range of energy sources in the future and enable greater reductions in air pollution.

Many other researchers from the U.S. and Europe have used an energy systems approach to understand the complex interactions among grid electricity sources. Table 1 lists 12 recent articles from the peer-reviewed, scientific literature, and briefly summarizes the conclusion from each report, on the pollution-reducing potential of wind energy.

All of the reports find that the addition of wind farms can reduce CO_2 emissions, although estimates vary widely.

Study Author	Location	Conclusion
Delarue and colleagues (2009) [2]	Belgium	Each megawatt (MW) of installed wind capacity could avoid 1,240 tons of CO_2 emissions, or about 500 kg CO_2/MWh.
Denny and O'Malley (2006) [3]	Ireland	800 MW of installed wind capacity (11% of Ireland's total capacity) could reduce CO_2 emissions by 9%. Adding wind to the grid did not substantially reduce SO_2 and NO_x emissions, but combining wind with a carbon tax did reduce SO_2 and NO_x.
Denny and O'Malley (2007) [4]	Ireland	The estimated benefits of integrating wind into the electricity grid exceed the estimated costs for wind installations up to about 20% of total capacity. The net benefits were about €1 billion ($1.3 billion) at nearly 2,000 MW of installed wind capacity.
Hart and Jacobson (2011) [5]	California	A low-carbon electricity portfolio (including wind) could reduce emissions by 80% relative to 2005.
Holttinen and Tuhkanen (2004) [6]	Nordic countries	Wind penetration of 4-12% displaces mostly coal and avoids CO_2 emissions at a rate of 700-620 g/kWh and a cost of €20-35/ton (about $26-46/ton).
Jacobson and High (2010) [7]	Upstate New York	The "time-matched marginal" method for calculating emissions is more accurate than other methods. In their N.Y. example, each 10,000 MWh of wind generation avoided 9,160 tons of CO_2 emissions
Kaffine and colleagues (2011) [8]	Midwest, Texas, California	In the Midwest Independent System Operator grid (including Michigan), 1 MWh of wind generation avoids 4.9 lbs. of SO_2, 2.0 lbs. of NO_x, and 1.0 tons of CO_2.
Katzenstein and Apt (2009) [9]	5 regions in U.S.	Displacement is not 1-to-1 because of backup reserves. Realized pollution reductions are likely 75-80% of simple estimates for CO_2, 30-50% for NO_x. Under the worst conditions, NO_x emissions actually increased under a 20% wind scenario.
Lu and colleagues (2011) [10]	Texas	30% wind penetration could result in a 58% reduction in CO_2 emissions (81 million tons per year) and could increase electricity price by $0.011/kWh. The marginal abatement cost of CO_2 reduction at 30% wind was $20/ton.
Luickx and colleagues (2010) [11]	Belgium	As wind capacity increases to 4.5 GW, CO_2 reductions range from 5% to 60% depending on the specific wind conditions.
Troy and colleagues (2010) [12]	Great Britain	Adding wind capacity increases system cycling, especially in baseload plants. At lower levels of wind penetration, adding storage capacity can increase cycling of baseload units. Storage becomes more favorable at high levels of wind penetration.
Ummels and colleagues (2007) [13]	Netherlands	Emissions of CO_2 and NO_x decline as wind penetration increases, up to a 25% reduction at 8 GW of wind capacity. SO_2 emissions decline only slightly. Load balancing problems can occur in systems with large amounts of combined heat and power which results in wasted wind energy. Wasted wind is insignificant below 4 GW (9.7% of total capacity)

Table 1: Peer-reviewed scientific articles on the pollution reduction potential of wind energy[1].

[1] The term "ton" can refer to either a "short ton" (2,000 lbs.) or a "metric ton" (1000 kg or 2,205 lbs.). Both are used in the literature on CO_2 emissions. The results reported in the table and elsewhere in the brief are in the units of the original article. No conversions have been made.

Wind farms may require that other power plants operate differently, which could affect energy use and emmissions.

All of the peer-reviewed reports listed in Table 1 concluded that wind energy can be integrated into the grid and that doing so reduces CO_2 emissions. None of the reports predict that wind energy would have no effect on air pollution. The addition of wind energy to the electricity grid, by itself, is less effective at reducing SO_2 and NO_x emissions than reducing CO_2. The addition of a carbon tax could change the way wind power displaces other energy sources with even greater benefits for air quality [4]. The amount of emissions reduction is highly sensitive to the mix of different types of power plants in a given region.

The amount of electricity produced by wind turbines fluctuates depending on wind speeds, which requires that other power plants increase their production when winds are slow. Katzenstein and Apt [9] noted that natural gas turbine fuel consumption (and NO_x emissions) could increase, depending on the type of turbine and on how the turbines are ramped up and down, when the gas turbines are quickly ramped up and down to balance the fluctuations of wind energy. When one kind of gas turbine was modeled, NO_x emissions fell, but not by as much as expected. When a different model of gas turbine was modeled, NO_x emissions increased relative to a zero-wind baseline. Keeping the gas turbine power levels above 50 percent minimized the ancillary, or additional, NO_x emissions. The study authors concluded if "system operators recognize the potential for ancillary emissions from gas generators used to fill in variable renewable power, they can take steps to produce a greater displacement of emissions [9]."

Most of Michigan's electricity, 75% in 2009, is generated by burning fossil fuels.

Potential Benefits for Michigan

Most of Michigan's electricity, 75 percent in 2009, is generated by burning fossil fuels: coal, natural gas, and relatively small amounts of petroleum and various other gases. In that same year, wind supplied 0.3 percent of Michigan's electricity (300,000 MWh) [14]. Generating electricity from fossil fuels emits greenhouse gases like carbon dioxide (CO_2), as well as pollutants that harm human health. In 2009 Michigan's electricity sector emitted 68 million metric tons of CO_2, more than 40 percent of Michigan's total emissions for that year [14].

Coal-fired power plants are most efficient when operating at a constant level, so they are typically used as "baseload sources", continually generating electricity for the grid.

The project team used two methods to estimate the emissions reduction potential of wind energy in Michigan. The first method is based on the Environmental Protection Agency's (EPA) Green Power Partnership Green Power Equivalency Calculator [16] and estimates for Michigan are presented in Table 2. The EPA calculator is a web-based tool that uses region-specific data from the EPA's eGRID energy and pollution database to estimate the degree to which wind energy (or other so-called green power) can displace emissions from non-baseload generation sources. Coal-fired power plants are most efficient when operating at a constant level, so they are typically used as "baseload sources", continually generating electricity for the grid. Natural gas plants are often a "non-baseload" source of electricity, because they can more easily ramp up and ramp down electricity production in response to varying power demands or varying levels of electricity coming from other sources such as wind farms.

Using the EPA calculator, the project team estimated how much carbon dioxide emissions would be reduced if a single 100 MW wind farm were built in Michigan's lower peninsula (the ReliabiltyFirst Corporation subregion). Wind farms typically operate at 20 to 35 percent of their capacity, depending on local wind conditions, so the team used four different estimated CO_2 reduction, capacity factors[2], for the calculations (Table 2).

A single 100MW wind farm could avoid the electricity-based CO_2 emissions from approximately 17,000 to 31,000 homes.

Capacity Factor[2]	Estimated Annual Electricity Output (kWh)	Estimated Annual CO_2 Emissions Reduction (tons)	Number of Households Supported by a 100 MW Wind Farm
20%	175,200,000	157,998	17,872
25%	219,000,000	197,499	22,340
30%	262,800,000	236,998	26,808
35%	306,600,000	276,498	31,276

Table 2: Estimated CO_2 reduction from integrating a 100 MW wind farm into Michigan's electricity grid

Table 2 illustrates that integrating wind energy into Michigan's electricity grid can reduce greenhouse gas emissions, even if wind energy displaces only non-baseload sources. A single 100 MW wind farm could avoid the electricity-based CO_2 emissions from approximately 17,000 to 31,000 homes. For example, one 100 MW wind farm could eliminate CO_2 pollution for the city of Muskegon, 16,105 housing units, or Oceana County, 15,944 housing units [17]. One 100 MW wind farm operating at a 20 percent capacity factor[2] would eliminate the average CO_2 emissions for either of these geographic areas.

Each MWh of wind energy added to the grid in midwest states avoided 4.9 pounds of SO_2, 2.0 pounds of NO_x, and 1.0 tons of CO_2.

As a comparison, we also estimated the potential air quality benefits of wind energy in Michigan using an alternate method based on the work of Kaffine and colleagues [8]. Kaffine's team used actual data from the Midwest Independent Operating System (MISO), the grid operator for the Midwest states including Michigan, to estimate how much pollution could be avoided by using wind energy. Their approach accounted for not only the marginal unit of generation displaced by wind, but also the marginal emissions from the displaced generation. The researchers found that each MWh of wind energy added to the MISO grid avoided about 4.9 pounds of SO_2, 2.0 pounds of NO_x, and 1.0 tons of CO_2. The MISO grid is more coal-dependent than Michigan, where 66 percent of the state's electricity was generated by coal in 2009. Accordingly, the pollution-reducing benefits would not be as significant to Michigan as they would be for the rest of the MISO grid [14].

The project team estimated the emission-reduction coefficient for Michigan's portfolio with 66 percent coal by interpolating from the graph in the article by Kaffine and colleagues. The team calculated that each MWh of Michigan-based wind energy would avoid air pollution emissions of about 3.5 pounds of SO_2, 1.5 pounds of NO_x, and 0.82 tons of CO_2. In 2009, Michigan's wind farms produced 300,172 MWh of electricity [15]. This corresponds to a reduction of:

- More than 1 million pounds of SO_2
- 450,000 pounds of NO_x
- 246,000 tons of CO_2

This estimate is consistent with the estimate from the EPA Green Power Partnership for a similar electricity output.

[2] Capacity factor refers to the proportion of electricity actually generated compared to a wind farm's maximum potential to produce electricity. For example, a 1 MW wind turbine operating at full capacity all the time for one year would produce 8,760 MWh of electricity, but that is unrealistic. If that turbine actually produced 2,628 MWh of electricity, its capacity factor would be 30% (2,628 / 8,760 *100% = 30%). Typical onshore wind farms range from 20% in modest wind areas to 40% in exceptional conditions.

In 2009, Michigan produced a total of 101 million MWh of electricity, ranked 6th among states in total SO_2 emissions, 6th in NO_x emissions, and 11th in CO_2 emissions.

In 2008, Michigan voted to enact a 10 percent Renewable Portfolio Standard (RPS); essentially a mandate that requires the State of Michigan to generate 10 percent of its electricity from renewable sources by 2015 [18]. In 2009, Michigan produced a total of 101 million MWh of electricity, ranked sixth among states in total SO_2 emissions, sixth in NO_x emissions, and eleventh in CO_2 emissions [19]. In 2009, the state received 3.9 percent of its electricity from renewable energy. If the remaining 6.1 percent of the renewable requirement were met with wind energy, Michigan could reduce substantial amounts of pollution, including a 6.9 percent potential reduction in CO_2 emissions from 2009 levels (Table 3).

	SO_2 (million lbs)	NO_x (million lbs)	CO_2 (million tons)
Total emissions in 2009	545.2	157.9	73.6
Estimated emissions reduction from existing renewable energy (3.9%)	-1.05	-0.45	-0.25
Estimated emissions reduction if another 6.1% of energy came from wind	-21.6	-9.3	-5.1
Percentage reduction if another 6.1% of energy came from wind	-4.0%	-5.9%	-6.9%

Table 3: Estimated pollution reduction that could be achieved by using wind energy to meet the remainder of Michigan's 10% renewable energy standard. Estimates based on framework by Kaffine et al. [8].

Power plants, including wind farms, also use electricity and generate pollution when they are being built, maintained and eventually demolished.

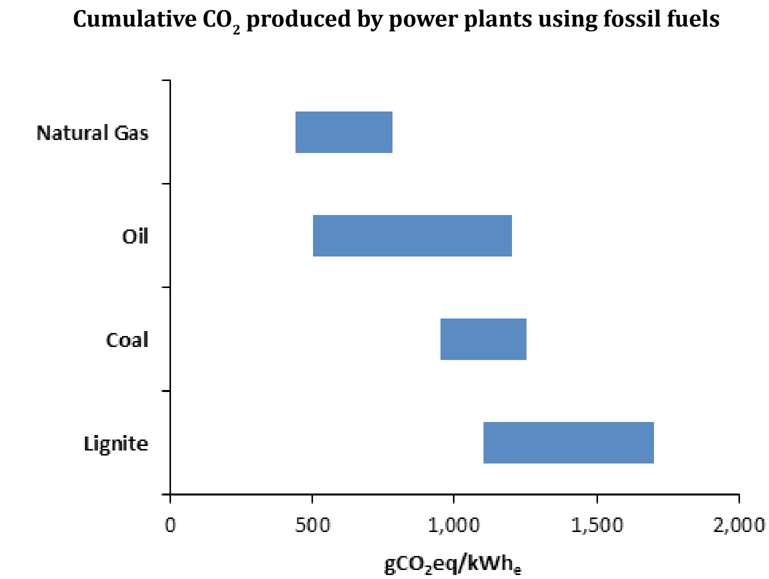
Emissions Output for a Wind Turbine: Cradle-to-Grave

Power plants, including wind farms, also use electricity and generate pollution when they are being built, maintained and then demolished at the end of their lifespan. Figure 2 shows the cumulative greenhouse gas emissions, from "cradle-to-grave[3]" for the most common electricity generation sources [20]. The units for comparing total emission are in grams of carbon dioxide equivalent[4] per kilowatt hour of electricity or gCO_2eq/kWh_e.

A majority of the greenhouse gas emissions (72-90%) associated with wind-generated electricity occurs when the turbines are being constructed. Offshore wind turbines require large amounts of concrete and steel for their foundations, so their construction produces more emissions than onshore wind turbines. A relatively small amount of emissions will occur while maintaining wind turbines. In contrast, the majority of the emissions associated with fossil fuel based electric generation occur during the operational phase of the power plant.

[3] Life cycle analysis (also known as a cradle-to-grave analysis) is a technique used to assess the environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

[4] Carbon dioxide equivalent is a metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential.



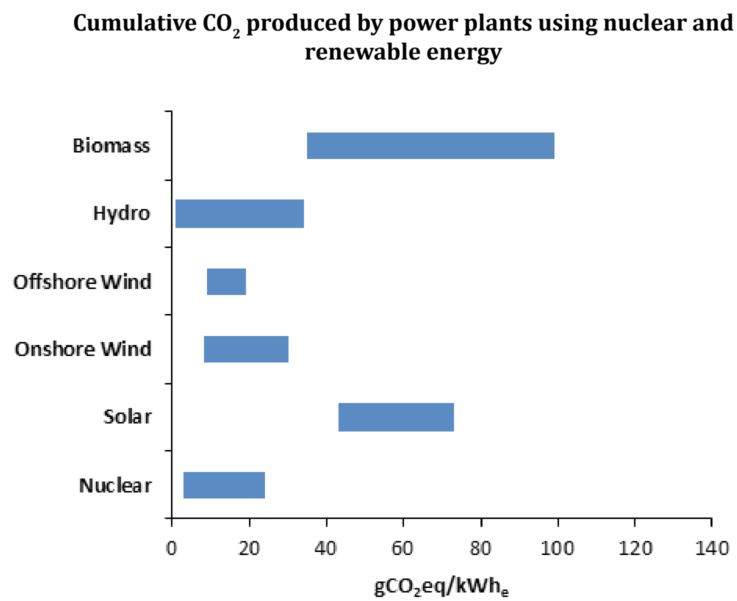


Figure 2: Cumulative carbon dioxide emissions from different types of energy facilities over the course of their lifespan. Note that the scale for CO_2 emissions is different for each graph [20].

One study found that the environmental pollution from wind turbine manufacturing, use, and decommissioning is offset by the benefits of operating the wind turbine for just one year.

Other scientists have reached similar conclusions on the life-cycle emissions of wind turbines. For example, Crawford and colleagues estimated that a 3.0 MW utility-scale wind turbine would avoid nearly 123,000 tons of greenhouse gas emissions over 20 years even after accounting for pollution emitted during turbine manufacturing and operation [21]. Martinez and colleagues found that the environmental pollution from wind turbine manufacturing, use and decommissioning is offset by its use in less than one year (its "energy payback") [22]. They also estimated that a 2 MW wind turbine produces 34 times more energy than is used in its manufacture, use and decommissioning.

Wind energy is not a silver bullet for Michigan's air pollution and climate challenges, but it can provide substantial benefits and is readily deployable.

Conclusion

Estimating the air quality improvements likely to result from building wind farms is not straightforward and different scientists and methods predict different results. If managed appropriately, wind energy has the potential to reduce the use of fossil fuels for generating electricity, which will reduce air pollution. Nearly all studies find that integrating wind energy will result in some reduction of conventional pollutant emissions such as SO_2 as well as greenhouse gases like CO_2. However, the air quality benefits of wind farms depends on the mix of existing energy sources. Over the short term, wind farms are more likely to reduce Michigan's reliance on natural gas than coal.

Wind energy is not a silver bullet for Michigan's air pollution and climate challenges, but it can provide substantial benefits and is readily deployable. Using wind energy to meet the remainder of Michigan's 10 percent renewable energy target could reduce CO_2 emissions by nearly 7 percent relative to 2009 levels. This level of wind deployment would also reduce SO_2 and NO_x, which would improve air quality. Life-cycle analyses have shown that a wind turbine can produce up to 34 times more energy than what went into manufacturing, operating and decommissioning the wind turbine.

The West Michigan Wind Assessment project team's focus has been on synthesizing existing data on key aspects of wind energy. The existing scientific literature shows that wind energy can be integrated into the grid, particularly at levels up to 10 percent of the total generating capacity, with pollution-reduction benefits. As more wind facilities come online in Michigan, future efforts can measure the benefits that result from Michigan's constructed wind farms.

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Principal Investigator: Erik Nordman, Ph.D.
Assistant Professor of Natural Resources Management
Grand Valley State University
nordmane@gvsu.edu

www.gvsu.edu/wind

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