WIND ENERGY AND HEALTH

APEX
CLEAN ENERGY

WIND ENERGY AND HEALTH

More than 52,000 wind turbines are in operation in the United States today, safely generating electricity for our nation. Wind energy is one of the healthiest forms of energy generation in the world because it releases no greenhouse gases, soot, or carbon into the atmosphere; it also does not consume valuable freshwater or produce water pollution. Apex wind projects are built in full compliance with local, state, and federal safety regulations to protect the health and welfare of landowners, maintenance teams, and others.

Key Findings from Health Impact Studies

Government- and university-sponsored studies around the world have repeatedly confirmed that modern, properly sited wind turbines pose no threat to public health. A growing number of studies reviewed by independent experts on wind energy and health have reached the same conclusion.

The World Health Organization, which classifies diseases, does not recognize wind turbine syndrome, nor does any other medical institution.

Wind Turbine Sound

The sound of wind turbine blades passing through the air is often described as a "whoosh." If properly constructed at approved setback distances, the sound does not result in any health concerns. Scientific evidence confirms that this sound is not detrimental and that any low-frequency or infrasound waves produced are not harmful to those nearby.[*]

Noise from wind turbines, including low-frequency noise and infrasound, is similar to noise from many other natural and human-made sources. There is no reliable or consistent evidence that proximity to wind farms directly causes health effects.[†]

"... infrasound emitted by wind turbines is minimal and of no consequence ... Further, numerous reports have concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines."[‡]

Shadow Flicker

This term refers to the shadows cast by wind turbine blades as they rotate in front of the sun. By positioning wind turbines at a carefully calculated angle and distance from dwellings, Apex ensures that most homes in a project experience no shadowing at all. For those that do, shadowing should occur for no more than a few minutes per day, on average. Shadowing does not occur on cloudy or foggy days.

While some have claimed that shadow flicker can create risk of seizures in photosensitive individuals, scientific evidence suggests that shadow flicker does not pose a risk of inducing seizures in people with photosensitive epilepsy.[‡]

The risk of ice striking a home 984 feet from a turbine is extremely low—researchers estimate that if it happens at all, it is only likely to occur once every 625 years.

*Journal of Occupational and Environmental Medicine, "Wind Turbines and Health-MIT," November 2014.
†Australian Government, National Health and Medical Research Council, "Evidence on Wind Farms and Human Health," February 2015.
‡Frontiers in Public Health, "Wind Turbines and Human Health," June 2014.

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Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005

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HIGHLIGHTS

- Ozone and PM impacts of the major combustion sectors in the U.S. are modeled.
- Early deaths attributable to each sector are estimated.
- ~200,000 early deaths occur in the U.S. each year due to U.S. combustion emissions.
- The leading causes are road transportation and power generation.

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ABSTRACT

Combustion emissions adversely impact air quality and human health. A multiscale air quality model is applied to assess the health impacts of major emissions sectors in United States. Emissions are classified according to six different sources: electric power generation, industry, commercial and residential sources, road transportation, marine transportation and rail transportation. Epidemiological evidence is used to relate long-term population exposure to sector-induced changes in the concentrations of $PM_{2.5}$ and ozone to incidences of premature death. Total combustion emissions in the U.S. account for about 200,000 (90% CI: 90,000–362,000) premature deaths per year in the U.S. due to changes in $PM_{2.5}$ concentrations, and about 10,000 (90% CI: −1000 to 21,000) deaths due to changes in ozone concentrations. The largest contributors for both pollutant-related mortalities are road transportation, causing ~53,000 (90% CI: 24,000–95,000) $PM_{2.5}$-related deaths and ~5000 (90% CI: −900 to 11,000) ozone-related early deaths per year, and power generation, causing ~52,000 (90% CI: 23,000–94,000) $PM_{2.5}$-related and ~2000 (90% CI: −300 to 4000) ozone-related premature mortalities per year. Industrial emissions contribute to ~41,000 (90% CI: 18,000–74,000) early deaths from $PM_{2.5}$ and ~2000 (90% CI: 0 –4000) early deaths from ozone. The results are indicative of the extent to which policy measures could be undertaken in order to mitigate the impact of specific emissions from different sectors — in particular black carbon emissions from road transportation and sulfur dioxide emissions from power generation.
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1. Introduction

Air pollution adversely affects human health (U.S. EPA, 2011a; WHO, 2006; COMEAP, 2010). The emission of pollutants into the atmosphere is an inherent by-product of combustion processes. Recent research has found that ambient concentrations of fine particulate matter (smaller than 2.5 μm in aerodynamic diameter, $PM_{2.5}$) (Dockery et al., 1993; Pope et al., 2002; WHO, 2006) and ozone (Bell et al., 2004; Jerrett et al., 2009; WHO, 2008a) are associated with the incidence of premature mortality and morbidity outcomes. Although other anthropogenic air pollutants are recognized as causes of adverse health impacts, ground level $PM_{2.5}$ and ozone exposure is currently considered the most significant known cause of early deaths related to poor outdoor air quality (U.S. EPA, 2011a). The U.S. Environmental Protection Agency estimated that in 2010 there were ~160,000 premature deaths in the U.S. due to $PM_{2.5}$ exposure and ~4300 deaths related to ozone exposure. Fann et al. (2012) estimated between 130,000 and 340,000 $PM_{2.5}$-related early deaths in 2005, and between 4700 and 19,000 ozone-related early deaths.

In the U.S., air pollution is regulated by the Clean Air Act and its amendments (1970 through 1990), which enables the EPA to set

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national air quality standards for six criteria air pollutants including $PM_{2.5}$ and ozone (U.S. EPA, 2011a). The Environmental Protection Agency estimated that in 2012 about 74 million people in the U.S. are exposed to levels of $PM_{2.5}$ higher than the limit standard and that more than 131 million live in regions not compliant with maximum allowable ozone levels (U.S. EPA, 2012b). The EPA computed the costs for the implementation of the 1990 Clean Air Act to be about 65 billion dollars, with a potential benefit reaching 2 trillion dollars from 1990 to 2020, potentially avoiding ~230,000 premature deaths in 2020 (U.S. EPA, 2011a). Although the CAA90 policy-implementation costs are distributed among different source categories, the attribution of air quality-related premature mortalities to different sectors has not been quantified in the peer-reviewed literature. An assessment of the early deaths attributable to different sources would create the potential to drive specific policies with the aim of maximizing the health benefits related to emission reductions from a certain economic activity. In the U.S., anthropogenic combustion emissions represent the predominant source of ground level $PM_{2.5}$ and ozone concentrations (U.S. EPA, 2011a).

In the first part of the present study we evaluate premature deaths attributable to U.S. combustion emissions represented by the following sectors: electric power generation, industry, commercial/residential activities, road transport, marine transport and rail transport. The contribution of $PM_{2.5}$ and ozone-related mortalities is quantified to inform policy makers about opportunities to diversify regulations by taking into account the health impact caused by different types of human activities. The second part of the study (Part II) will focus on assessing future-year combustion emissions impacts from different sectors and on future possible mitigation strategies.

2. Data and methodology

The health impacts of combustion emissions from different sectors are evaluated through the derivation of a temporally, spatially and chemically resolved emissions inventory in the contiguous United States (CONUS), and parts of Canada and Mexico for the reference year 2005. Meteorology and air quality models are used to relate emissions to pollutant concentrations. A baseline simulation, including all emission sources, is performed to assess the model capability to predict meteorological fields, particulate matter and ozone concentrations. Sector emission scenarios are developed wherein combustion emissions from each of the six emission sectors defined above are removed in turn from the baseline inventory; differences in particulate matter and ozone concentrations between the baseline and sector scenario simulations are attributed to the contribution of that specific sector. Population exposure to sector-attributable $PM_{2.5}$ and ozone concentrations are used with concentration-response functions (CRFs) to estimate premature mortality impacts of each sector.

The calculated mortalities can be seen as potentially avoidable deaths in the reference year 2005 related to the instantaneous removal of combustion emissions from each specific sector. An extensive discussion about the use of number of premature deaths per year as a metric for anthropogenic health impact assessments is given by the UK Committee on the Medical Effects of Air Pollutants (COMEAP, 2010). The approach adopted in this study follows the methodology for the evaluation of "current" health burdens from air pollution described by COMEAP (2010). The remainder of this section details each of the steps previously described.

2.1. Meteorological modeling

The modeling domain is centered about the CONUS, including parts of Canada and Mexico. The horizontal resolution is 36 km (112 rows by 148 columns), with 34 sigma-pressure vertical layers. Meteorological fields for the year 2005 are derived using the Weather Research and Forecasting Model (WRF version 3.3.1; Skamarock et al., 2008), driven by four-dimensional data assimilation from the six-hourly NCEP Final Analyses (FNL) data at $1^\circ \times 1^\circ$ resolution. Meteorological simulations are validated against direct hourly temperature and wind observations from 1672 and 1619 stations, respectively. Observations are collected by the Meteorological Assimilation Data Ingest System (MADIS, 2010), developed by the National Oceanic and Atmospheric Administration (NOAA).

2.2. Emissions

Baseline emissions in the U.S., Canada and Mexico are derived from the 2005 EPA National Emissions Inventory (NEI; U.S. EPA, 2008a). This represents the most up to date emissions inventory at the time of this study. NEI 2005 emissions are compiled using data from numerous state and local agencies. The Sparse Matrix Operator Kernel Emissions program version 2.6 (SMOKE, 2010) is used to prepare emissions for the air quality model. SMOKE applies chemical speciation profiles (in case of PM, NO_x and Volatile Organic Compounds), temporal profiles and spatial surrogates for allocation of emissions into model grid-cells. The spatial surrogates are compiled by the EPA (SMOKE, 2010) to allocate area and line sources (which are often specified as county totals) to the CMAQ model grid cells. The emissions are distributed using area-weighting, and the emission allocation is done based on source classification codes (SCCs).

Pre-processed WRF meteorological fields are used to treat emissions from mobile sources for which emissions factors are significantly influenced by local temperature and relative humidity (Ashok, 2011) as well as to compute the plume rise of point-source emission sources and vertically allocate them into the model layers. Emissions scenarios are developed for six source categories ("sectors"): (a) electric power generation, (b) industry, (c) commercial/residential, (d) road transportation, (e) marine transportation, (f) rail transportation. Sectors are defined with differences relative to EPA source categories (U.S. EPA, 2008b) including that commercial and residential sources are merged together and transportation is divided into three separate sectors (discussed later). The division of the transportation sector is performed in order to capture contributions from different modes of transportation and assess modal emission mitigation strategies in future years in the second part of the study.

Sector emissions are taken out from each scenario by removing, in turn, the sources associated to the specific sector from the baseline NEI dataset. Aviation emissions are included in the baseline case, but aviation is not explicitly considered as a sector here since the premature mortalities related to this specific sector have been assessed in Yim et al. (2013). Sector-attributable emissions are considered only in the CONUS together with the U.S. maritime exclusive economic zone (200 nmi off the coastline, plus maritime boundaries with adjacent/opposite countries). Emissions from Canada and Mexico are kept in all the simulations at their original baseline values. We thus focus our investigation on the health impacts on U.S. population from sources located within the U.S. territory. The CONUS and maritime boundary specifications are taken from the National Atlas of the United States of America (2012) and from the Office of Coast Survey (OCS) of the NOAA (1998).

Totals for primary particulate matter, NO_x and SO_2 emissions for the reference year 2005 from each of the sectors are given in Table 1. Combustion emissions from the sectors considered account for 82% of the NO_x anthropogenic emissions in the continental U.S., and 98% of the sulfur dioxide emissions. Emissions from fugitive dust, agricultural activities, aviation and other non-combustion sources are not considered in the sector specifications.

Table 1
$PM_{2.5}$ (primary), NO_x and SO_2 emissions totals and percentages with respect to the baseline scenario (NEI, 2005 dataset, including all sources). Emissions are expressed in Tg year^{-1} for each sector considered in the study (data for 2005).

Sector	$PM_{2.5}$		NO_x		SO_x	
	Total	%	Total	%	Total	%
Electric power generation	0.46	11.7%	3.42	16.1%	9.46	70.4%
Industry	0.57	14.5%	2.75	13.0%	2.55	19.0%
Commercial/residential	0.69	17.6%	0.76	3.6%	0.49	3.6%
Road transportation	0.27	6.9%	8.17	38.5%	0.16	1.2%
Marine transportation	0.07	1.8%	1.30	6.1%	0.45	3.4%
Rail transportation	0.03	0.8%	1.01	4.8%	0.07	0.5%
Other	1.84	46.8%	3.81	18.0%	0.25	1.9%
Total	3.93	100.0%	21.22	100.0%	13.43	100.0%

It is possible to relate the totals found from the 2005 NEI to more recent estimates by using yearly total emissions trends for air pollutants in the U.S. (U.S. EPA, 2012a). The trends estimated by EPA indicate that with respect to 2005, in 2012 SO_2 emissions would be ~60% lower, NO_x emissions ~40% lower, and VOC emissions ~15% lower, while $PM_{2.5}$ and ammonia emissions are expected to increase by ~14% and ~5% respectively. We note that these figures are preliminary estimates and, particularly for SO_2 and NO_x, may be significantly revised.

2.3. Air quality modeling

Air quality simulations for the year 2005 are performed using the CMAQ (version 4.7.1) regional chemistry-transport model (Byun and Schere, 2006) at a spatial resolution of 36 km × 36 km. A two-week spin-up time is used to mitigate the influence of initial conditions. The initial and boundary conditions for the CMAQ simulations are provided by Barrett et al. (2012). Simulated $PM_{2.5}$ baseline concentrations are validated against 24-h averaged observations from 543 stations collected by the EPA Speciation Trends Network (STN). Ozone baseline concentrations are validated against hourly data from 538 stations from the U.S. EPA Air Quality System (AQS) (U.S. EPA, 2011b).

2.4. Health impacts

Epidemiological studies have quantified the relationship between adverse health effects and long-term exposure to $PM_{2.5}$ (U.S. EPA, 2011a; Lewtas, 2007; Krewski et al., 2009; Laden et al., 2006) and ozone (Bell et al., 2004; Jerrett et al., 2009). The quantitative association between premature mortality and ground-level concentrations of $PM_{2.5}$ and ozone is generally assessed through the derivation of relative risk (RR) factors and concentration-response functions (CRFs). An expert elicitation by the U.S. EPA reports a decrease of 1% (range 0.4%–1.8%) in annual all-cause deaths for a 1 μg m^{-3} decrease in the annual average $PM_{2.5}$ exposure in the United States (U.S. EPA, 2011a). Similar results are reported for Europe (Cooke et al., 2007). Jerrett et al. (2009) associated long-term ozone exposure with the risk of death from respiratory causes. In that study, the relative risk of early death from respiratory diseases as a consequence of an increase in ozone concentration of 10 ppb is estimated as 1.040 (95% confidence interval, 1.010–1.067).

$PM_{2.5}$ and ozone account for the majority of monetary losses related to the health impacts of air pollution (Ratliff et al., 2009), and as such long-term exposure to $PM_{2.5}$ and ozone form the focus of the present study. Premature deaths in the U.S. related to sector-attributable $PM_{2.5}$ are estimated using a linear CRF based on EPA assessments (U.S. EPA, 2011a) and described further in Barrett et al. (2012). The CRF associates long-term exposure to $PM_{2.5}$ with premature deaths from cardiopulmonary causes and lung cancer. For long-term exposure to ozone, a log-linear CRF derived from the results of Jerrett et al. (2009) is adopted, consistent with previous ozone health impact assessments in the U.S. (U.S. EPA, 2011a; Fann et al., 2012). The CRF evaluates the number of premature deaths Δy corresponding to a change in ozone concentration ΔO_3 (Abt Associates Inc. and U.S. EPA, 2012). Specifically,

$$\Delta y = y_0 \cdot \left(1 - \frac{1}{\exp(\beta \cdot \Delta O_3)}\right) \tag{1}$$

where y_0 is the baseline incidence rate of the health effect (death from respiratory diseases). The change in ozone concentration ΔO_3, specified in ppb, represents a change in the daily maximum ozone concentration averaged during the ozone season (April 1 – September 30), as described in Jerrett et al. (2009). The coefficient β takes on specific values for urban areas as well as region-specific values for rural areas based on the following geographical regions of the U.S.: Northeast, Industrial Midwest, Southeast, Upper Midwest, Northwest, Southwest, Southern California, as defined by the EPA (Krewski et al., 2000). Nominal values of β and standard error estimates used for uncertainty quantification are provided by the EPA (Abt Associates Inc. and U.S. EPA, 2012). For both $PM_{2.5}$ and ozone, mortalities are evaluated as single sector contributions for adults over 30 years old. Baseline incidences for pollutant-related mortalities (cardiopulmonary diseases and lung cancer for the $PM_{2.5}$ CRF, respiratory diseases for the ozone CRF) are taken from the WHO Global Burden of Disease (WHO, 2008b). Population density is retrieved from the Gridded Population of the World database (GPWv3, 2004).

2.5. Uncertainty assessment

The uncertainties inherent in the premature mortality calculations, including uncertainties from the CRF parameters as well as the air quality modeling, are quantified in this study. For $PM_{2.5}$ – related mortality calculations, the uncertainty in the CRF is accounted for with a triangular probability distribution of multiplicative factors with (low, nominal, high) values of (0.3, 1, 1.7) (U.S. EPA, 2006). The low, nominal and high values correspond to the vertices of the triangular distribution function. The distribution of CMAQ model normalized mean biases is used to account for the uncertainty in predicting PM concentrations, and it is modeled as a normal distribution of mean 7.55% and standard deviation of 28.1%. The minimum (−67.2%) and maximum (108.1%) normalized mean biases are adopted as limiting values to trim the tails of the normal distribution. The reciprocal of the biases distribution are used as multiplicative factors to correct CMAQ model predictions in the uncertainty calculations.

We note that the uncertainty related to different toxicities among $PM_{2.5}$ species as well as a ~10% probability of no causal link between $PM_{2.5}$ exposure and premature mortality (Roman et al., 2008) have not been accounted for quantitatively in this study. The assumption of equal toxicities is consistent with U.S. EPA expert elicitation studies (U.S. EPA, 2004), but represents an unquantified uncertainty (Levy et al., 2009). A similar approach is applied for the uncertainty assessment of ozone-related premature mortalities. For the ozone CRF shown in Equation (1) we consider a triangular probability distribution of multipliers with (low, nominal, high) values of ($\beta - 1.96\,\sigma_\beta$, β, $\beta + 1.96\,\sigma_\beta$), as tabulated in Abt Associates Inc. and U.S. EPA, 2012. The values σ_β of correspond to the standard errors for the health impact estimates performed by the CRF in different regions of the U.S. (Abt Associates Inc. and U.S. EPA, 2012). The β coefficients and their corresponding standard errors vary between each of the seven geographical regions of the U.S.

Table 2
Statistical model evaluation of WRF (wind speed and temperature) and CMAQ ($PM_{2.5}$ and ozone) against observations. Wind speed and temperature are evaluated on an hourly basis, $PM_{2.5}$ on a 24-h average, and ozone is evaluated as daily maximum values recorded during the ozone season (Apr–Sept). The units for each quantity are indicated in the table.

	Wind [m s^{-1}]	T [°C]	$PM_{2.5}$ [μg m^{-3}]	Ozone [ppb]
Model Mean	3.58	12.93	13.85	55.01
Model SD	2.14	11.76	9.39	15.74
Observed Mean	3.32	12.88	12.98	56.74
Observed SD	2.46	11.89	8.49	17.88
Index of Agreement	0.82	0.98	0.69	0.74
Correlation	0.68	0.97	0.49	0.57
Annual Mean Bias (%)	8.02	0.39	6.77	−3.04
Root-mean-square error	1.88	2.90	9.13	15.87
Mean Bias	0.22	0.05	0.88	−1.72
Mean Normalized Bias (%)	10.17	1.25	28.60	2.62
Normalized Mean Bias (%)	8.02	0.39	6.77	−3.04
Mean Fractional Bias (%)	30.24	10.42	1.90	−1.96
Mean Error	1.45	2.17	6.53	11.62
Normalized Mean Gross Error (%)	43.67	16.86	50.33	20.47
Mean Normalized Gross Error (%)	42.47	12.02	63.01	22.37
Mean Fractional Error (%)	65.47	−8.92	49.46	21.10
Data Availability (%)	74.74	76.94	73.73	98.12

described in Section 2.4. As such, the ozone CRF uncertainty bounds are computed individually for each of the regions. Region-specific uncertainty for the CMAQ ozone predictions is calculated using a normal distribution of normalized mean biases. Mean value, standard deviation and limits of the distributions are computed for each region following the same approach as for the $PM_{2.5}$-related model uncertainty evaluation.

3. Results

3.1. Model evaluation

Meteorological and air quality simulations are validated against observations using a set of statistical metrics recommended by the EPA (U.S. EPA, 2005). The definitions for each of the metrics can be found in Yim and Barrett (2012): in particular, an index of agreement (IA) of 1 indicates perfect agreement between the model and the available observations.

Overall the simulated meteorology and air quality statistics, shown in Table 2, are within the range or close to recent studies adopted for similar applications (Yim and Barrett, 2012; Gilliam and Pleim, 2010). Simulated wind speed (measured in m s^{-1}) exhibits an index of agreement of 0.82 and a normalized mean bias around 8% with respect to the available observations. Modeled temperature (measured in °C) shows an IA of 0.98 and a positive bias of 0.39%. The 24-h averaged fine particulate matter (in μg m^{-3}) computed by CMAQ has an index of agreement of 0.69. For ozone, daily maximum values (in ppb) during the ozone season (Apr–Sept) are computed, showing an index of agreement of 0.74. The model estimates the concentrations of $PM_{2.5}$ and ozone with a normalized mean bias of 6.77% and −3.04% respectively. The daily maximum evaluation of ozone during the ozone season yields a normalized mean gross error of 20.47%. Considering all the monitoring stations, the highest bias for the ozone seasonal daily maximum is 61%, the minimum is −42%. These values, computed in each of the seven U.S. regions that characterize the discrete application of the ozone CRF (1), are used as limits for the model uncertainty computations. The annual mean $PM_{2.5}$ modeling bias for all stations exhibits a maximum value of 108% and a minimum of −67%: as noted in

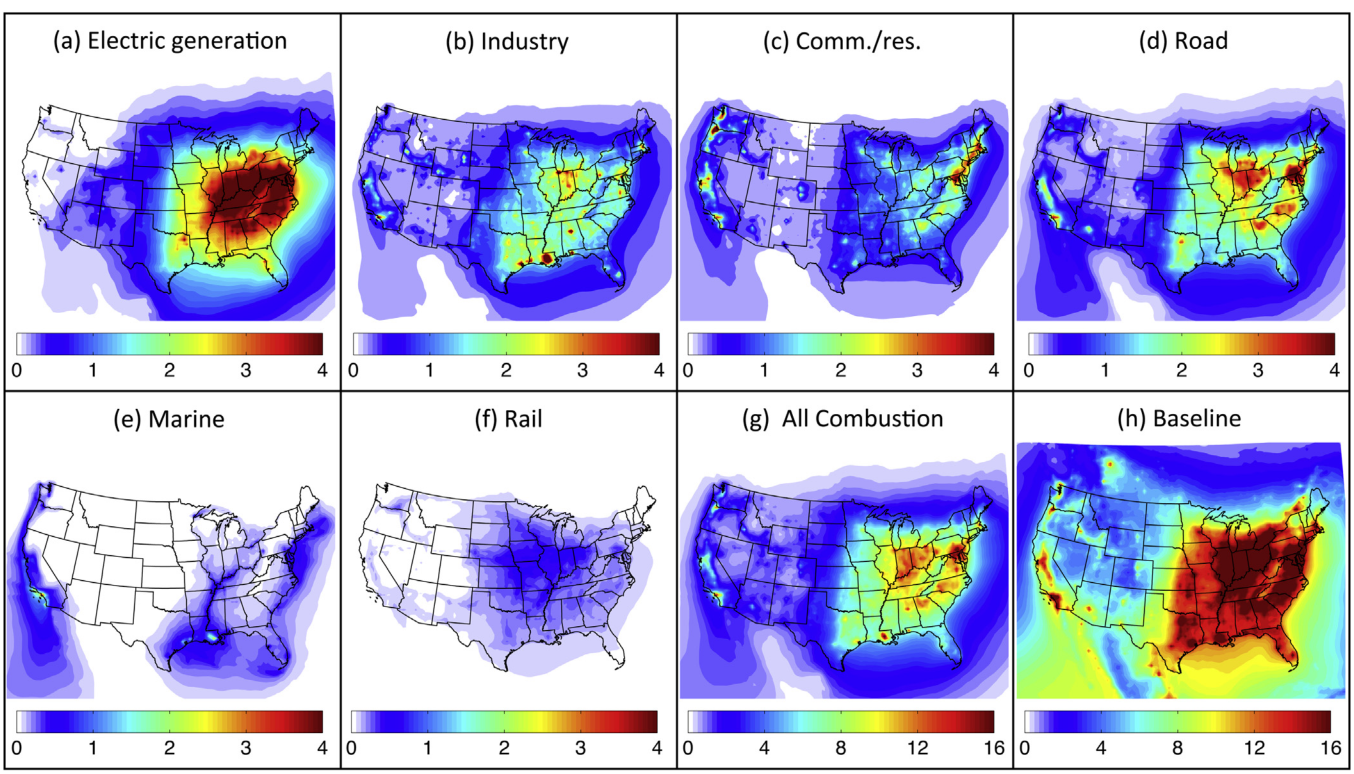

Fig. 1. Annual average ground-level $PM_{2.5}$ concentration (μg m^{-3}) from U.S. sources attributable to combustion emissions from (a) electric power generation; (b) industry; (c) commercial and residential sources; (d) road transportation; (e) marine transportation; (f) rail transportation; (g) sum of all combustion sources; (h) all sources (baseline case for this study). A different scale is adopted for (a–f) and (g–h).

Table 3
Population-weighted concentrations of $PM_{2.5}$ (μg m^{-3}) and ozone (ppb) attributable to combustion emissions from the six sectors considered in this study. $PM_{2.5}$ population-weighted annual mean concentration is speciated into six categories: sulfate (Sulf), nitrate (Nit), ammonium (Amm), black carbon (BC), organics (Org) and unspeciated (Uns). The total concentration of $PM_{2.5}$ is displayed in the second last column of the table. The PM concentrations are annually averaged while the ozone concentration is evaluated as daily maximum averaged over the ozone season (Apr–Sept).

Sector	$PM_{2.5}$							Ozone
	Sulf	Nit	Amm	BC	Org	Uns	Total $PM_{2.5}$	
Electric power generation	1.13	0.05	0.36	0.01	0.48	0.24	2.27	2.15
Industry	0.41	0.19	0.19	0.04	0.42	0.52	1.78	2.06
Commercial/residential	0.13	0.12	0.08	0.08	0.93	0.47	1.82	0.67
Road transportation	0.10	0.61	0.25	0.27	0.98	0.08	2.30	6.90
Marine transportation	0.11	0.03	0.04	0.06	0.09	0.03	0.36	0.39
Rail transportation	0.01	0.05	0.02	0.03	0.09	0.00	0.20	0.53
Total from combustion	1.89	1.05	0.94	0.49	2.99	1.34	8.73	12.70

section 2.4, these values are used as uncertainty ranges in the CMAQ $PM_{2.5}$ evaluation.

3.2. $PM_{2.5}$ impacts

Annual average ground-level $PM_{2.5}$ attributable to U.S. emissions from the different sectors considered in this study is shown in Fig. 1. The general distribution of particulate matter concentrations highlights the clustering of anthropogenic activities along the coastlines and in the Midwest regions of the U.S.

Table 3 shows the population-weighted annual mean concentrations of $PM_{2.5}$ (together with its composite species) and ozone attributable to the different sectors. Road transportation is responsible for a $PM_{2.5}$ population-weighted concentration of 2.30 μg m^{-3} in U.S., representing the largest contributor to PM-related impacts. Most of the particulate matter attributable to road transport emissions is organic (0.98 μg m^{-3}) followed by nitrate aerosol (0.61 μg m^{-3}): this reflects the fact that onroad mobile emissions are the largest source of NO_x in the U.S., as shown in Table 1. Vehicle emissions are also the largest contribution to population-weighted black carbon concentrations (0.27 μg m^{-3}). The change in black carbon concentration attributable to road vehicles in the U.S. is shown in Fig. 2a. BC concentrations peak in major cities where the traffic is higher, in contrast to total $PM_{2.5}$ concentrations (Fig. 1d) which are more diffuse due to the inclusion of secondary particulate matter. For this reason, black carbon from road emissions has a relatively high adverse health impact with respect to other PM species.

Electric power generation is responsible for a population-weighted annual mean $PM_{2.5}$ concentration of 2.27 μg m^{-3}. Given the discrete distribution of power plants, the contribution of this sector is less ubiquitous with respect to road transportation (Fig. 1a), being less relevant on the western regions. Power plants account for 16% of NO_x emissions and 70% of SO_2 emissions in the U.S. (Table 1). Of the 9.46 million tons of sulfur dioxide emitted in 2005, about 95% comes from coal-fired power plants (NRDC, 2007) which represent the largest source of electricity in the U.S. (U.S. EIA, 2012).

Eastern power plants generally use coal with higher sulfur content than western power plants (U.S. EIA, 2002). This trend is shown in Fig. 2b, which displays the ground-level annual mean sulfate concentration attributable to electric generation. In the Midwest states, the sulfate concentration exhibits peaks of 3.5 μg m^{-3}, which account for the 1.13 μg m^{-3} population-weighted concentration of sulfate due to the electric sector. Yim and Barrett (2012) reported a population-weighted mean annual sulfate concentration of about 0.25 μg m^{-3} in the UK, showing a significantly smaller impact of the electric generation sector in this country with respect to what we found in the U.S. This is partially due to the fact that the largest power plants in the UK are generally located relatively far away as well as downwind from highly populated regions.

Combustion emissions from commercial and residential sources generate a mean annual population-weighted $PM_{2.5}$ concentration of 1.82 μg m^{-3}, mostly composed of organic particulate matter (0.93 μg m^{-3}). Due to the nature of these sources, the peaks in commercial/residential contributions occur in the most densely populated areas of the east and the west coast (Fig. 1c).

Fig. 1b shows mean $PM_{2.5}$ concentrations due to emissions from industrial activities, which account for a population-weighted annual concentration of 1.78 μg m^{-3}. The concentration distribution exhibits peaks in the Midwest industrial area between Chicago and Detroit, and in the regions around Philadelphia, Atlanta and Los Angeles. The largest contributions occur in the coastline of the U.S. Gulf Coast connecting Mobile (AL), New Orleans (LA) and Houston (TX). The high concentration of industry-attributable $PM_{2.5}$ in this

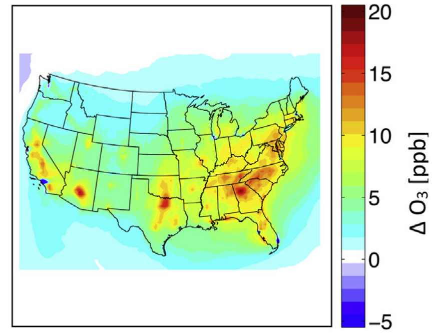

Fig. 3. Variation of mean (Apr–Sept) daily maximum ozone concentration (ppb) due to road transportation emissions in 2005.

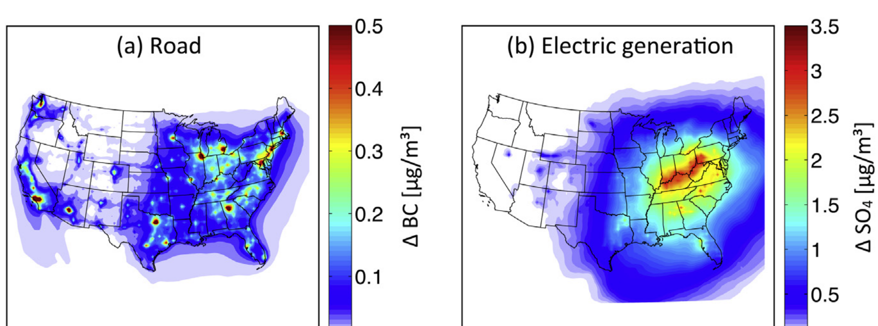

Fig. 2. Annual average ground-level concentration (in μg m^{-3}) in the U.S. of (a) black carbon (BC) due to road transportation; (b) SO_4 due to electric power generation.

Table 4
Premature deaths [90% confidence interval] in the U.S. in 2005 due to long-term exposure to $PM_{2.5}$ and ozone associated to combustion emissions from different sectors.

Sector	$PM_{2.5}$	O_3
Electric power generation	52,200 [23,400–94,300]	1700 [−250–3700]
Industry	40,800 [18,300–73,700]	1750 [−30–3500]
Commercial/residential	41,800 [18,700–75,500]	350 [−50–750]
Road transportation	52,800 [23,600–95,300]	5250 [−850–11,100]
Marine transportation	8300 [3700–15,000]	530 [−50–1100]
Rail transportation	4500 [2000–8100]	540 [−100–1200]
Aviation (Yim et al., 2013)[a]	1200 [550–2600]	155 [71–260]
Total from combustion[b]	200,400 [89,700–361,900]	10,100 [−1300–21,400]

[a] Refers to global full flight emission impact in the U.S., using the same CRFs described in Section 2.4.
[b] Excluding aviation.

region is related to the presence of the largest oil refineries in the United States (U.S. EIA, 2004).

Mean annual concentrations of particulate matter due to marine emissions are shown in Fig. 1e. Emission sources are considered only within the maritime exclusive economic zone (200 nmi off the coastline, plus maritime boundaries with adjacent/opposite countries), and Southern California exhibits their largest impact in terms of $PM_{2.5}$ concentration. Particulate matter forming in this region as a consequence of maritime emissions is then substantially advected to the southeast. Locally significant marine transportation-attributable $PM_{2.5}$ concentrations span along all the U.S. coastlines and along the navigable portions of the Mississippi and Ohio rivers. The population-weighted annual average concentration of total $PM_{2.5}$ is 0.38 $\mu g\ m^{-3}$, and is almost equally distributed between different PM species.

Finally, Fig. 1f shows the $PM_{2.5}$ concentration due to rail emissions: rail-attributable particulate matter spreads relatively

Table 5
Number of premature mortalities (NM) and mortality rate (MR) per year due to $PM_{2.5}$ concentrations attributable to different sectors in the 48 states of the CONUS (plus District of Columbia). Mortality rate (MR) corresponds to number of deaths per year per 100,000 people within the state.

State	Electric gen		Industry		Comm/Res		Road		Marine		Rail	
	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR
Alabama	1242	27.3	833	18.3	509	11.2	766	16.8	86	1.9	83	1.8
Arizona	127	2.5	269	5.3	386	7.6	616	12.1	41	0.8	37	0.7
Arkansas	630	23.7	410	15.4	219	8.2	411	15.4	56	2.1	72	2.7
California	468	1.3	4834	13.9	6459	18.6	5726	16.4	3484	10.0	280	0.8
Colorado	177	4.1	160	3.7	388	9.0	264	6.2	5	0.1	24	0.6
Connecticut	473	13.9	332	9.7	821	24.1	697	20.5	62	1.8	25	0.7
Delaware	248	31.4	162	20.5	179	22.7	230	29.2	35	4.4	12	1.6
DC	187	35.1	76	14.2	164	30.8	150	28.2	7	1.3	8	1.5
Florida	2402	15.1	1372	8.6	1045	6.6	1852	11.7	459	2.9	106	0.7
Georgia	2335	28.3	1232	15.0	1161	14.1	1809	22.0	103	1.2	141	1.7
Idaho	13	1.0	127	9.6	112	8.5	68	5.1	4	0.3	10	0.8
Illinois	3161	25.0	2840	22.5	1551	12.3	3135	24.8	176	1.4	437	3.5
Indiana	2032	32.8	1661	26.8	838	13.5	1639	26.5	100	1.6	209	3.4
Iowa	528	17.7	379	12.7	235	7.9	476	16.0	22	0.7	101	3.4
Kansas	448	16.2	365	13.2	211	7.6	396	14.3	15	0.5	99	3.6
Kentucky	1642	39.7	726	17.6	556	13.5	886	21.4	86	2.1	101	2.4
Louisiana	826	18.2	1133	24.9	319	7.0	568	12.5	314	6.9	74	1.6
Maine	98	7.5	81	6.2	192	14.7	105	8.1	14	1.1	3	0.3
Maryland	1885	34.9	987	18.3	1505	27.9	1558	28.8	104	1.9	96	1.8
Massachusetts	821	12.8	1211	18.8	1775	27.6	1368	21.3	131	2.0	42	0.7
Michigan	2289	22.3	1858	18.1	1050	10.2	2484	24.2	103	1.0	196	1.9
Minnesota	580	11.6	664	13.3	559	11.2	777	15.6	38	0.8	122	2.4
Mississippi	684	23.7	431	14.9	241	8.3	414	14.3	82	2.8	56	1.9
Missouri	1329	23.3	873	15.3	588	10.3	1048	18.4	82	1.4	196	3.4
Montana	8	0.8	24	2.7	26	2.8	18	1.9	1	0.1	4	0.5
Nebraska	227	13.1	168	9.7	92	5.3	193	11.1	6	0.3	57	3.3
Nevada	47	2.4	109	5.6	98	5.0	104	5.3	16	0.8	10	0.5
New Hampshire	137	10.9	176	14.0	279	22.2	185	14.7	12	1.0	6	0.5
New Jersey	1885	22.2	1260	14.8	2341	27.6	2420	28.5	328	3.9	78	0.9
New Mexico	63	3.4	79	4.4	85	4.7	97	5.3	5	0.3	14	0.8
New York	3744	19.8	2400	12.7	4442	23.5	4730	25.1	559	3.0	176	0.9
North Carolina	2570	32.0	1059	13.2	1196	14.9	1742	21.7	115	1.4	134	1.7
North Dakota	35	5.3	26	4.0	19	2.9	25	3.8	1	0.1	9	1.4
Ohio	4223	36.1	2024	17.3	1783	15.3	3054	26.1	204	1.7	328	2.8
Oklahoma	536	15.3	466	13.3	224	6.4	489	14.0	26	0.7	78	2.2
Oregon	35	1.0	238	6.8	1263	36.3	252	7.3	82	2.3	24	0.7
Pennsylvania	3864	31.1	2118	17.1	2431	19.6	3114	25.1	274	2.2	193	1.6
Rhode Island	145	14.1	128	12.5	237	23.1	178	17.3	20	2.0	6	0.6
South Carolina	1196	29.3	532	13.1	575	14.1	846	20.8	60	1.5	66	1.6
South Dakota	70	9.2	55	7.2	29	3.8	51	6.7	1	0.2	14	1.9
Tennessee	1787	31.1	928	16.2	641	11.2	1053	18.3	95	1.7	117	2.0
Texas	2835	13.4	3583	17.0	1869	8.8	3239	15.3	642	3.0	317	1.5
Utah	58	2.6	88	3.9	107	4.8	145	6.5	6	0.3	10	0.5
Vermont	57	9.2	36	5.8	69	11.2	56	9.1	3	0.5	3	0.5
Virginia	2433	33.8	1153	16.0	1416	19.7	1608	22.4	121	1.7	120	1.7
Washington	50	0.8	308	5.1	1625	26.9	554	9.2	149	2.5	38	0.6
West Virginia	683	36.5	269	14.4	243	13.0	307	16.4	23	1.2	31	1.6
Wisconsin	981	17.9	728	13.3	770	14.1	1083	19.8	52	1.0	130	2.4
Wyoming	15	3.0	23	4.7	9	1.8	10	2.1	1	0.1	3	0.6

Table 6
Number of premature mortalities (NM) and mortality rate (MR) per year due to $PM_{2.5}$ concentrations attributable to different sectors in the 20 most populous metropolitan areas (M) and cities (C) of the CONUS (2005 data). Mortality rate (MR) corresponds to number of deaths per year per 100,000 people within the state.

City/MA	Electric gen		Industry		Comm/Res		Road		Marine		Rail	
	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR
New York City (M)	2571	20.3	1713	13.5	3555	28.0	3615	28.5	483	3.8	103	0.8
Los Angeles (M)	137	1.5	1854	20.6	1891	21.1	2092	23.3	1505	16.8	90	1.0
Chicago (M)	1102	22.7	1378	28.4	716	14.8	1379	28.4	56	1.1	171	3.5
Detroit (M)	657	23.2	593	21.0	292	10.3	790	27.9	28	1.0	46	1.6
Philadelphia (M)	573	27.1	404	19.1	535	25.3	591	28.0	79	3.7	25	1.2
Boston (M)	242	12.4	546	28.0	682	35.0	540	27.7	47	2.4	13	0.7
Washington (M)	655	35.2	290	15.6	560	30.1	533	28.6	24	1.3	32	1.7
San Jose (M)	11	0.6	202	11.0	433	23.4	199	10.8	126	6.8	8	0.4
Houston (M)	255	14.1	506	27.9	258	14.2	304	16.8	158	8.7	25	1.4
San Diego (M)	56	3.4	143	8.7	339	20.7	288	17.5	201	12.3	12	0.7
Minn.-Saint Paul (M)	203	12.5	318	19.5	253	15.5	341	20.9	13	0.8	43	2.6
Dallas (M)	280	17.4	329	20.5	209	13.0	374	23.2	20	1.3	29	1.8
Baltimore (M)	475	34.7	368	26.9	441	32.2	430	31.4	35	2.6	25	1.8
Phoenix (C)	34	2.6	89	7.0	141	11.1	225	17.7	11	0.8	11	0.8
Cleveland (M)	466	36.8	222	17.6	222	17.5	384	30.3	32	2.5	37	2.9
Miami (C)	127	10.2	70	5.6	80	6.4	128	10.3	61	4.9	5	0.4
Denver (M)	53	4.4	50	4.2	128	10.7	103	8.6	1	0.1	7	0.6
Saint Louis (M)	280	26.8	204	19.5	141	13.5	235	22.5	22	2.1	31	2.9
Kansas City (C)	208	20.1	163	15.8	109	10.6	199	19.2	8	0.7	47	4.5

uniformly in the central-eastern part of the U.S., with a peak in the Midwest. Yearly averaged population-weighted concentration of rail-attributable $PM_{2.5}$ is 0.20 μg m^{-3}.

3.3. Ozone impacts

The impact on ozone concentrations is related to the atmospheric concentrations of VOC and NO_x. Fig. 3 shows the average daily maximum concentration of ozone attributable to road transportation emissions. Daily maximum ozone is temporally averaged only during the ozone season (Apr–Sep), consistent with EPA practice. Road mobile emissions induce a domain-wide increase in daily maximum seasonal ozone concentrations, except for some major urban areas (e. g. Miami), where the high background NO_x concentrations account for a decrease in the ozone concentrations due to the additional NO_x emitted by road vehicles.

Road transportation provides the most significant impact over ozone exposure among the combustions emission sources considered in this study. From Table 3, the population-weighted mean daily maximum ozone concentration due to vehicle emissions is 6.90 ppb, about three times larger than the population-weighted concentration change due to electric generation (2.15 ppb) and industry (2.06 ppb). Commercial/residential activities, as well as shipping and rail emissions, have an impact on the mean daily maximum ozone concentration below 1 ppb.

3.4. Health impacts

Premature deaths from cardiovascular diseases and lung cancer due to long-term exposures to $PM_{2.5}$ attributable to each sector are evaluated by applying the CRF described in Section 2.4, and are given in Table 4. Aggregated combustion emissions account for a total of about 200,000 (90% CI: 90,000–361,000) $PM_{2.5}$-related premature mortalities per year in the U.S. This result is comparable with total mortalities estimated by similar studies (U.S. EPA, 2011a; Fann et al., 2012). The distribution of early deaths among the different sectors reflects the population-weighted average $PM_{2.5}$ sector-attributable concentrations shown in Table 3.

The two largest contributors to $PM_{2.5}$-related premature deaths in the U.S. are road transport and power generation, accounting for 53,000 (90% CI: 24,000–95,000) and 52,000 (90% CI: 23,000–94,000) early deaths per year, respectively.

Commercial/residential sources and industry account for 42,000 (90% CI: 19,000–76,000) and 41,000 (90% CI: 18,000–74,000) early deaths, respectively. About 8000 (90% CI: 4000–15,000) deaths per year are attributable to marine transport and 4500 (90% CI: 2000–8000) to rail transport. Aviation mortalities are included in the table as estimated by Yim et al. (2013): a total of 1200 (90% CI: 550–2600) $PM_{2.5}$-related mortalities per year are attributable to full flight aviation emissions in North America.

Table 5 allocates the $PM_{2.5}$-related premature mortalities for each sector shown in Table 4 in the 48 states (and the District of Columbia) of the CONUS. This table displays for each state both the absolute number of premature deaths per year and the mortality rate, defined as number of early deaths per year per 100,000 people within the state.

CMAQ gridded results for each sector are attributed to each state using the code ArcGIS (ESRI, 2008). In terms of absolute impact of $PM_{2.5}$ combustion emissions, the most affected region is California, with about 21,000 early deaths per year. Of these, about 12,000 come from both commercial/residential sources and road transportation, and ~5000 from industry. About 3500 premature deaths per year in this state are attributable to marine transportation emissions, which exhibit a peak in Southern California (Fig. 1e).

The data in Table 5 show a large impact of electric generation emissions in the central-eastern U.S. and in the Midwest. This reflects the trend shown in Fig. 2b for power generation-related sulfate concentrations. In particular, with a mortality rate (MR) of about 40 premature deaths per year per 100,000 inhabitants in Kentucky, electric generation is the sector responsible for the highest mortality rate among the U.S. states.

Road transportation, consistent with its annual mean $PM_{2.5}$ concentration map (Fig. 1d), exhibits the most widespread distribution of sector-attributable premature deaths among the U.S. states. In terms of relative impacts, the state characterized by the highest relative mortality due to all the sectors is Maryland, with about 114 early deaths per year every 100,000 inhabitants.[1]

[1] It should be noted that the total number of early deaths given in Table 5 for each sector does not exactly coincide with the values of Table 4 for the whole U.S. This is due to slight inaccuracies in the allocation of the gridded population distribution within state boundaries, which yields an average error of 0.9% in the estimate of the cumulative number of deaths per each sector.

Table 7
Number of premature mortalities (NM) and mortality rate (MR) per year due to ozone concentrations attributable to different sectors in the 48 states of the CONUS (plus District of Columbia). Mortality rate (MR) corresponds to number of deaths per year per 100,000 people within the state.

State	Electric gen		Industry		Comm/Res		Road		Marine		Rail	
	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR
Alabama	97	2.13	69	1.51	14	0.31	240	5.27	22	0.49	24	0.52
Arizona	41	0.81	47	0.92	19	0.37	403	7.94	16	0.32	30	0.59
Arkansas	50	1.90	46	1.72	6	0.21	120	4.53	15	0.56	18	0.66
California	8	0.02	43	0.12	22	0.06	209	0.60	49	0.14	12	0.03
Colorado	27	0.62	23	0.54	3	0.08	57	1.33	1	0.03	7	0.17
Connecticut	−2	−0.06	−2	−0.07	−1	−0.04	−12	−0.35	−1	−0.02	0	−0.01
Delaware	−1	−0.08	−1	−0.07	0	−0.03	−3	−0.36	0	−0.03	0	−0.02
DC	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Florida	175	1.10	97	0.61	82	0.52	191	1.20	9	0.06	22	0.14
Georgia	108	1.31	77	0.94	19	0.23	396	4.80	24	0.30	28	0.34
Idaho	2	0.15	6	0.43	1	0.07	16	1.20	1	0.07	2	0.17
Illinois	12	0.09	9	0.07	2	0.01	24	0.19	3	0.02	5	0.04
Indiana	−1	−0.01	0	−0.01	0	0.00	−3	−0.04	0	0.00	0	0.00
Iowa	46	1.56	36	1.20	6	0.20	97	3.24	5	0.18	19	0.64
Kansas	44	1.57	43	1.56	4	0.16	88	3.20	5	0.16	17	0.61
Kentucky	24	0.58	13	0.30	2	0.06	48	1.15	5	0.11	5	0.13
Louisiana	65	1.44	109	2.40	8	0.18	163	3.58	75	1.66	17	0.38
Maine	−1	−0.05	−1	−0.07	−1	−0.04	−5	−0.36	0	−0.04	0	−0.01
Maryland	−4	−0.07	−3	−0.06	−1	−0.02	−16	−0.29	−1	−0.02	−1	−0.02
Massachusetts	−3	−0.05	−2	−0.04	−2	−0.03	−4	−0.06	−1	−0.02	0	0.00
Michigan	−1	−0.01	−1	−0.01	0	0.00	−3	−0.03	0	0.00	0	0.00
Minnesota	54	1.08	42	0.84	9	0.18	119	2.39	6	0.12	21	0.42
Mississippi	51	1.76	50	1.73	6	0.22	135	4.68	26	0.91	16	0.55
Missouri	72	1.25	48	0.85	8	0.14	144	2.52	12	0.21	26	0.46
Montana	2	0.20	2	0.26	0	0.04	8	0.92	1	0.06	2	0.17
Nebraska	26	1.48	23	1.33	2	0.14	48	2.75	2	0.11	12	0.70
Nevada	2	0.12	4	0.19	1	0.08	20	1.05	1	0.07	2	0.11
New Hampshire	−1	−0.05	−1	−0.05	0	−0.03	−4	−0.28	0	−0.01	0	−0.01
New Jersey	−2	−0.03	−3	−0.04	−2	−0.02	−3	−0.04	1	0.01	0	−0.01
New Mexico	40	2.22	55	3.03	5	0.30	127	7.02	5	0.28	19	1.06
New York	−7	−0.04	−9	−0.05	−5	−0.03	−16	−0.09	2	0.01	−2	−0.01
North Carolina	150	1.86	98	1.22	31	0.38	489	6.08	32	0.40	33	0.41
North Dakota	8	1.16	5	0.79	1	0.11	12	1.78	0	0.07	3	0.52
Ohio	−2	−0.02	−1	−0.01	0	0.00	−6	−0.05	0	0.00	0	0.00
Oklahoma	72	2.06	95	2.71	9	0.25	222	6.33	13	0.37	25	0.71
Oregon	4	0.10	7	0.21	4	0.13	36	1.03	8	0.23	3	0.08
Pennsylvania	−10	−0.08	−7	−0.06	−3	−0.02	−37	−0.30	−1	−0.01	−2	−0.02
Rhode Island	−1	−0.07	−1	−0.06	0	−0.04	−4	−0.40	−1	−0.05	0	−0.01
South Carolina	73	1.79	53	1.30	15	0.36	260	6.38	20	0.50	18	0.43
South Dakota	12	1.58	10	1.30	1	0.14	21	2.75	1	0.11	6	0.73
Tennessee	101	1.76	67	1.17	13	0.23	277	4.82	23	0.39	27	0.48
Texas	252	1.19	495	2.34	43	0.20	1052	4.98	163	0.77	88	0.42
Utah	9	0.42	6	0.27	1	0.06	27	1.21	1	0.05	3	0.13
Vermont	0	−0.07	0	−0.07	0	−0.03	−2	−0.39	0	−0.02	0	−0.02
Virginia	39	0.54	22	0.31	7	0.09	69	0.95	−20	−0.28	7	0.10
Washington	3	0.05	5	0.08	4	0.06	29	0.48	3	0.05	2	0.04
West Virginia	−1	−0.03	0	−0.01	0	−0.01	−2	−0.08	0	0.00	0	0.00
Wisconsin	15	0.27	12	0.21	3	0.05	33	0.61	3	0.05	6	0.10
Wyoming	4	0.82	4	0.72	0	0.07	7	1.37	0	0.05	2	0.31

Table 6 shows the same results as Table 5 for the 20 most populous metropolitan areas in the U.S. Urban population data are retrieved from the National Atlas of the United States, 2005. As expected for all metropolitan areas, road transportation and commercial/residential sources have the largest and most uniformly distributed impact on all cities. The highest peaks of the $PM_{2.5}$-related health impacts due to vehicle emissions are found in the major East coast cities: New York (MR ~ 28.5), Washington (MR ~ 28.6) and Baltimore (MR ~ 31.4). The city of Baltimore in particular is characterized by the highest total mortality rate from all combustion sources: about 130 early deaths attributable to $PM_{2.5}$ per year per 100,000 inhabitants. The highest absolute all-combustion sources impact is in New York, with about 12,000 total mortalities per year.

Of the set of 5695 cities considered, the highest $PM_{2.5}$-attributable all-combustion mortality rate (MR ~144) has been found in Donaldsonville, LA. Here the presence of nine oil refineries within a 70-km radius, for a total production of ~2.2 million barrels per day (NREL, 2012), accounts for a mortality rate by industrial sources of ~81 early deaths per year per 100,000 people.

Table 4 also includes premature mortalities due to ozone concentrations attributable to the different sectors. Aggregated combustion emissions account for about 10,100 (90% CI: −1300 to 21,400) ozone-related premature deaths in the U.S. in 2005. As with $PM_{2.5}$, the aggregate ozone mortality estimate is consistent with previous national emissions assessments in the U.S. (U.S. EPA, 2011a; Fann et al., 2012). The negative lower bound is a consequence of the ozone depletion occurring in densely populated cities, due to NO_x emissions in NO_x-saturated environments.

The main contributor is road transportation, which is responsible for more than half of the ozone-related mortalities (~5250). Both electric generation and industry account for about 1800 mortalities per year. Commercial/residential, marine and rail transport account for about 350, 530 and 540 ozone-related mortalities annually, respectively. It is noted that, despite their relatively large contributions to $PM_{2.5}$ mortalities with respect to the other sectors, commercial and residential sources contribute only to a fraction of the total ozone-related early deaths. This can be explained by considering the NO_x emission attributions given in Table 1. Road transportation represents the single largest contributor to NO_x emissions (accounting for 38.5% of the total). Industry and electric generation both give a similar contribution to NO_x emissions. This trend is reflected in the national pattern of ozone-related mortalities shown in Table 4.

Similarly to the previous tables for $PM_{2.5}$, Table 7 and Table 8 provide the number of early deaths per year and the mortality rate due to ozone exposure as a consequence of emissions from the six sectors considered. Table 7 shows the data for each U.S. state, while Table 8 sorts the results for the 20 most populous metropolitan areas. The correlation between high ozone levels and high sunlight exposure, together with differences in emissions and background VOC and NO_x concentrations, account for the uneven distribution of ozone-related mortalities between northern and southern states.

More than 20% of the ozone-related mortalities from all sectors (~2100 early deaths) occur in Texas, mainly as a consequence of road transportation and industrial emissions. The second most affected state is North Carolina, with about 800 ozone-related early deaths per year, half of which attributable to vehicle emissions. Smaller states with high percentage of urban areas (e. g., Maryland, Connecticut) are characterized by an ozone-related mortality reduction due all-sectors emissions. In these regions, ozone is generally depleted by additional NO_x emissions. The same principle applies to many of the metropolitan areas considered in Table 8.

4. Discussion

The spatial distribution and speciation of $PM_{2.5}$ impacts per sector can be used to inform the design of sector-specific emission mitigation measures. Premature mortalities from sulfate attributable to power plants represent approximately half of the ~52,000 mortalities from the sector. These mortalities are mainly related to SO_x emissions from coal power plants, and could be reduced by promoting the purchase of low-sulfur content coal from the western deposits in the Powder River Basin in Wyoming and Montana (Stavins and Schmalensee, 2012), the introduction of lime scrubbers, or the adoption of alternative energy sources (e. g. natural gas, as forecasted by the U.S. EIA, 2012). Similarly, the mortalities related to marine combustion emissions (of which about one third is related to sulfate concentrations) could be reduced by enforcing limits to the sulfur content of bunker fuel used in ship engines. Regulations to this effect have recently been put in place by the International Maritime Organization (IMO, 2010). In 2010 a limit of 1% fuel sulfur content for the North America Emission Control Area (ECA) was established, to be lowered to 0.1% in 2015.

In using the results of this study to inform potential mitigation measures, it is important to note that premature mortality estimates are calculated assuming equal toxicity amongst the different types of particulate matter. Recent epidemiological studies (Lippmann and Chen, 2009; Levy et al., 2012) suggest that differential toxicity amongst PM species may be significant. In an extensive multi-site time-series analysis, Levy et al. (2012) showed differences in the correlations between changes in hospital admissions and concentrations of different types of $PM_{2.5}$, with black carbon showing the highest relative health impact. Furthermore, a recent ACS cohort analyses (Lippman, 2010) indicate that $PM_{2.5}$ correlations with premature mortality risk may vary with source category, with coal and traffic sources having the most significant associations. Despite these findings, no epidemiological study to date has provided a conclusive assessment of the relative toxicity of different $PM_{2.5}$ components, sufficient to develop CRFs accounting for those differences [as per Levy et al. (2012) and current EPA practice]. It is therefore possible that future CRFs will be able to describe particulate matter health impacts by weighting PM species. Table 3 of the present study provides data appropriate for such a calculation.

An assessment of the health impacts from $PM_{2.5}$ and ozone concentrations attributable to different source categories in the US has been performed in parallel with the present study by Fann et al. (2013), who adopt a source apportionment approach to allocate the concentrations of $PM_{2.5}$ and ozone among various different source categories. Their source categories follow the NEI source classification scheme, whereas we have reprocessed inventories to correspond to what may be termed "economic" sectors. For example, the "industrial" sources in this study are split between "industrial point sources" and "area sources" in Fann

Table 8
Number of premature mortalities (NM) and mortality rate (MR) per year due to ozone concentrations attributable to different sectors in the 20 most populous metropolitan areas (M) and cities (C) of the CONUS (2005 data). Mortality rate (MR) corresponds to number of deaths per year per 100,000 people within the state.

City/MA	Electric Gen		Industry		Comm/Res		Road		Marine		Rail	
	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR	NM	MR
New York City (M)	−2.22	−0.017	−4.66	−0.037	−2.67	−0.021	3.76	0.030	2.93	0.023	−0.53	−0.004
Los Angeles (M)	0.24	0.003	1.42	0.016	1.52	0.017	0.95	0.011	0.02	0.000	−0.17	−0.002
Chicago (M)	−0.13	−0.003	−0.12	−0.002	0.01	0.000	0.23	0.005	−0.01	0.000	0.06	0.001
Detroit (M)	−0.02	−0.001	−0.02	−0.001	−0.01	0.000	−0.02	−0.001	0.00	0.000	0.00	0.000
Philadelphia (M)	−0.16	−0.008	−0.15	−0.007	−0.07	−0.003	−0.75	−0.035	−0.06	−0.003	−0.03	−0.002
Boston (M)	−0.42	−0.021	0.10	0.005	−0.19	−0.010	8.96	0.459	0.19	0.010	0.21	0.011
Washington (M)	−0.77	−0.041	−0.67	−0.036	−0.28	−0.015	−3.57	−0.192	−0.11	−0.006	−0.21	−0.011
San Jose (M)	0.21	0.012	1.33	0.072	0.78	0.042	5.19	0.281	6.05	0.328	0.08	0.004
Houston (M)	9.17	0.505	22.37	1.233	3.24	0.179	47.30	2.607	11.25	0.620	2.78	0.153
San Diego (M)	0.02	0.001	0.28	0.017	0.11	0.007	0.13	0.008	−0.50	−0.031	0.05	0.003
Minn.-Saint Paul (M)	9.40	0.577	6.20	0.380	1.63	0.100	21.49	1.318	0.87	0.053	3.54	0.217
Dallas (M)	4.15	0.258	6.22	0.386	0.60	0.037	16.92	1.051	1.46	0.091	1.19	0.074
Baltimore (M)	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
Phoenix (C)	4.48	0.351	6.68	0.523	3.89	0.305	71.07	5.569	2.53	0.198	4.65	0.364
Cleveland (M)	−0.08	−0.006	−0.06	−0.005	−0.02	−0.002	−0.03	−0.002	0.03	0.003	0.01	0.001
Miami (C)	0.83	0.067	8.09	0.651	12.71	1.024	−94.1	−7.582	−13.11	−1.056	0.41	0.033
Denver (M)	3.28	0.275	2.77	0.231	0.68	0.057	11.07	0.926	0.18	0.015	0.93	0.078
Saint Louis (M)	−0.04	−0.004	−0.03	−0.003	−0.01	−0.001	−0.19	−0.018	−0.01	−0.001	−0.01	−0.001
Kansas City (C)	8.55	0.827	5.03	0.486	0.83	0.081	14.76	1.429	0.83	0.080	3.01	0.291

et al. (2013), where their area sources in turn also include part of the commercial/residential emissions considered in this study. Here we make a comparison for $PM_{2.5}$-related early deaths insofar as possible using Table 3 of the Fann et al. (2013) SI and assuming a nominal 12 life years lost per premature mortality for the purposes of this comparison. We note that these comparisons are not like-for-like due to the different inventory processing applied (as well as different meteorology and air quality models, and apportionment approach) and it is not clear the extent to which comparisons are appropriate. For power generation [Fann et al. (2013): electricity generating units] we estimate 52,200 early deaths per year, compared to their 51,700 using our conversion. For mobile sources [approximately our road transportation, marine transportation, rail transportation and aviation] we estimate 66,800 early deaths per year, cf. their estimate of 36,300. We note that our aircraft estimate includes cruise emissions, whereas theirs is based on a different inventory and only for landing and takeoff emissions. For industry [Fann et al. (2013): all industrial sub-categories except electricity generating units] we estimate 40,800 cf. their 22,400. However, our definition of industry includes some of their "area sources" so an upper bound on their early deaths would be 42,800. In total (excluding non-anthropogenic and transboundary pollution) Fann et al. (2013) estimates 148,000 early deaths per year, cf. our 200,000 early deaths per year. This implies that our estimates are broadly ~35% higher, although firm conclusions about individual sectors cannot be made. Additionally, we infer 16 life years lost per premature mortality for electricity generating units from their work which would expand the difference by ~30%, while our accounting for low $PM_{2.5}$ modeling biases in our probabilistic approach would serve to reduce the effective differences by ~25%. On a relative basis, we observe that in both assessments electric generation accounts for about 25% of the total $PM_{2.5}$ premature deaths. The relative importance of the aggregated transportation sectors (road, marine, rail and aviation) in the present study is higher (~33% versus ~20%) than the "mobile" sector considered in Fann et al. (2013).

5. Conclusions

Combustion emissions in the U.S. are found to be responsible for ~200,000 premature mortalities due to long-term exposure to increased $PM_{2.5}$ concentrations, and ~10,600 premature mortalities due to exposure to increased ozone concentrations. The totals computed do not consider non-linearities in the model response (e. g., in the formation of secondary $PM_{2.5}$). This effect is expected to be relatively small, potentially yielding an underestimation in total mortalities of the order of 6%, as found in a study using an analogous methodology in the United Kingdom (Yim and Barrett, 2012).

Among the different sectors considered in this study, road transportation accounts for the largest number of early mortalities, ~53,000 $PM_{2.5}$-related and ~5300 ozone-related. For comparison, we consider that in 2005 the number of fatalities related to car accidents in the U.S. was ~43,500 (U.S. DOT, 2012). This suggests that the air quality impact of road transportation in terms of premature deaths may likely exceed the number of fatal accidents by about 30%. It is documented (U.S. DOT, 2012) that about 40% of the fatal accidents involve people in the 0–44 years range, corresponding to a loss of about 35 life years per fatality. Emissions instead generally affect people at older ages, with an average loss of ~12 years per mortality (COMEAP, 2010), yielding a total of 0.70 million life years lost from both $PM_{2.5}$ and ozone exposure per year. This means that car accidents may still be the leading cause of loss of life years, despite the smaller number of fatalities. These issues related to the use of premature mortalities as a metric to assess the health burden related to air pollution are discussed in COMEAP (2010).

Considering concentrations of different types of $PM_{2.5}$, road vehicles account for a population-weighted concentration of black carbon larger than the sum of all the other sectors (Table 3).

Power generation emissions results in adverse health impacts similar to road transportation in terms of premature mortalities (Table 3). A large extent of this impact is related to sulfur dioxide emissions from coal-fired power plants. The population-weighted concentration of 1.13 $\mu g\ m^{-3}$ of sulfate due to electric generation is the highest among all the $PM_{2.5}$ species for all the sectors considered (Table 2). A reduction of sulfur dioxide emissions from power plants could therefore limit the adverse health impact of electric generation, and should be taken into account for future U.S. energy and air quality policies.

The extent of the impact on air quality by road transportation and electric power generation found in this assessment will drive the selection of future-year mitigation scenarios explored in Part II of the study.

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The Clean Air Benefits of Wind Energy

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Executive Summary

Wind energy is a widely available, affordable, reliable, non-emitting, readily quantifiable and verifiable, and rapidly deployable electric generation method for significantly reducing air pollution, including emissions of carbon dioxide (CO_2), nitrogen oxides (NOx) and sulfur dioxide (SO_2). Indeed, the current fleet of wind turbines in the U.S. is already reducing carbon emissions by nearly 127 million tons per year.

In May 2014, the U.S. Global Change Research Program (USGCRP)[1] issued its National Climate Assessment.[2] The report documents the existing evidence and impacts of climate change here at home, including on a regional basis as well as on specific sectors like energy and human health. Wind energy is specifically identified as one of the available mitigation options.

Similarly, the U.N. Intergovernmental Panel on Climate Change[3] issued several volumes that make up its Fifth Assessment Report[4] earlier this year, which found a need to triple or nearly quadruple electric generation from zero- and low-carbon energy resources by 2050 in order to avert the worst consequences of climate change.

The U.S. Environmental Protection Agency (EPA) also notes the following about the benefits from reducing SO_2 and NOx: "By reducing SO_2 and NO_x, many acidified lakes and streams will significantly improve so that they can once again support fish life. Visibility will improve, allowing for increased enjoyment of scenic vistas across our country, particularly in National Parks. Stress to our forests that populate the ridges of mountains from Maine to Georgia will be reduced. Deterioration of our historic buildings and monuments will be slowed. Most importantly, reductions in SO_2 and NO_x will reduce fine particulate matter (sulfates, nitrates) and ground level ozone (smog), leading to improvements in public health."[5]

In order to address the aforementioned challenges and pursuant to decisions by the U.S. Supreme Court, the EPA in June 2014 will propose a rulemaking to, for the first time ever, provide for federal limits on carbon pollution from existing power plants under section 111(d) of the Clean Air Act.[6] States will play a key role in the compliance process with the final rule, in part through the submission of state plans that will detail how generators in their states will meet the carbon pollution standards set forth by the EPA.

As detailed in this white paper, wind energy is widely available across the country as a compliance option under 111(d) and is already playing a significant role in reducing carbon emissions in nearly every state, as well as emissions of other air pollutants. Further, as also described in the following pages, wind energy is doing so affordably and reliably for consumers.

Of particular note, this paper provides state-by-state numbers, calculated using the EPA's own Avoided Emissions and generation Tool (AVERT), for the emissions reductions

1 The USGCRP is made up of 13 federal agencies and departments.
2 A team of more than 300 experts guided by a 60-member Federal Advisory Committee produced the report, which was extensively reviewed by the public and experts, including federal agencies and a panel of the National Academy of Sciences. The report is available online at: http://nca2014.globalchange.gov/
3 http://www.ipcc.ch/
4 http://www.ipcc.ch/report/ar5/index.shtml
5 Available at: http://www.epa.gov/airmarkets/progsregs/arp/basic.html#bens
6 For more information, see: http://www2.epa.gov/carbon-pollution-standards

attributable to the currently installed wind turbine fleet in the U.S.

Among the key findings in this paper:

- The 167.7 million megawatt-hours (MWh) of wind energy produced in the U.S. in 2013 reduced CO_2 emissions by 126.8 million tons, the equivalent of reducing power sector emissions by more than 5 percent, or taking 20 million cars off the road.

- The top 10 states by volume of carbon reductions from wind energy are: Texas, Illinois, California, Colorado, Iowa, Missouri, Oklahoma, Wisconsin, Minnesota and Wyoming.

- States achieving a reduction in carbon emissions of 10 percent or more from wind energy alone include California, Colorado, Idaho, Iowa, Kansas, Minnesota, Nebraska, Oregon, South Dakota, Vermont, and Washington State, with Oklahoma, Wisconsin and Wyoming coming in just under 10%.

- One MWh of wind energy avoids .75 tons, or 1,500 pounds, of carbon dioxide emissions on average. A typical 2 MW wind turbine avoids around 4,000-4,500 tons of carbon emissions annually, equivalent to the annual carbon emissions of more than 700 cars.

- Wind energy currently reduces SO_2 emissions by nearly 347 million pounds per year and NO_x by 214 million pounds per year.

- Wind energy saved 36.5 billion gallons of water in 2013 that would have been consumed at conventional power plants, the equivalent of roughly 116 gallons per person in the U.S., or 276 billion bottles of water, providing critical relief in drought-stricken areas.

- There are 61,110 megawatts (MW) of wind energy capacity installed in 39 states and Puerto Rico, representing more than 46,000 operational utility-scale wind turbines. There are now 16 states with 1,000 MW or more of installed wind energy capacity.

- Over the last five years, wind energy has accounted for 31 percent of all newly installed electric generating capacity, second only to natural gas. In 2012, wind energy was the largest source of all new generating capacity at 42 percent.

- In some regions, such as the Pacific Northwest, Plains states and the Midwest, wind energy has been the primary source of new capacity over the last three years, providing 60 percent or more of all new electric generating capacity. In the Upper Midwest, wind energy provided more than 80 percent of all new generating capacity from 2011-2013.

- The existing wind turbine fleet provides the electrical output equivalent to 53 average coal plants or 14 average nuclear plants.

- On an average annual basis, wind energy produces more than 25 percent of the electricity in two states, 12 percent or more in nine states, and five percent or more in 17 states.

- The average power purchase price of wind energy has fallen 43 percent over the last 5 years, with both the Energy

Information Administration and Lazard finding that wind energy is second only to a combined cycle natural gas plant in terms of lowest cost source of new electric generation.

- While other generation may need to ramp up or down to accommodate the variability of wind energy (and other far larger sources of variability on the power system like electricity demand and the sudden failure of large conventional generators), two recent studies from different regions in the U.S. document that such cycling has virtually no net effect on the emissions reductions from wind energy, with wind producing 99.8 percent of the carbon emissions savings expected of a zero emissions resource.

- Wind energy can play an even greater role in reducing emissions reductions going forward. More than a dozen utility and independent grid operator studies have found wind can reliably provide an even larger share of our electricity needs, which will, in turn, produce even larger emissions reductions. For example, an NREL study for the Eastern U.S. found that obtaining 20 percent of electricity from wind energy cut power sector carbon emissions by 25 percent, and 30 percent wind cut carbon emissions by 37 percent, relative to the baseline generation mix.

- Wind energy can continue to rapidly scale up. Since the end of 2005, the U.S. wind energy industry has doubled its installed capacity, on average, every 36 months. The U.S. industry installed a high of more than 13,000 MW in 2012, and there are currently more wind projects under construction in the U.S. than at any point in history. U.S. wind energy's five year average annual growth rate is 19.5 percent from 2009-2013.

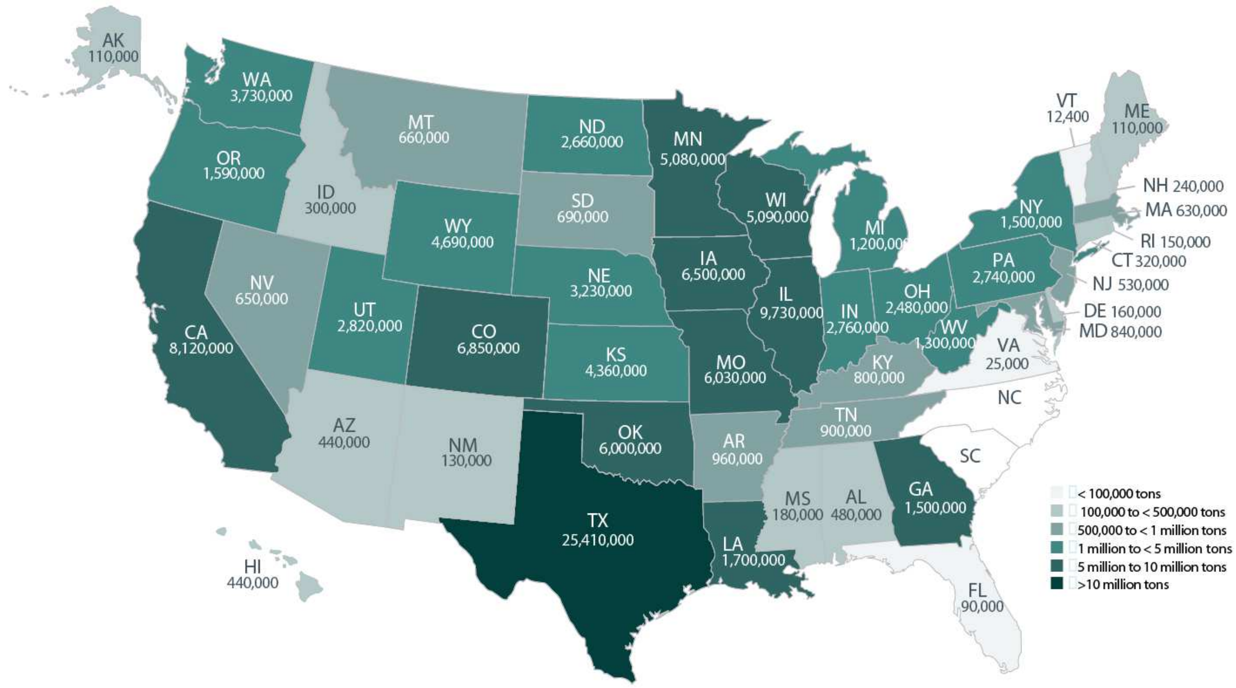

Figure 1: Wind energy's 2013 emissions reductions by state, using EPA's AVERT tool[7]

Wind energy is greatly reducing emissions of carbon dioxide and other pollutants in nearly every state.

AWEA used a new EPA modeling tool to quantify the state-by-state pollution reductions wind energy is currently providing, and the results are shown in the map and tables below. The 167.7 million megawatt-hours (MWh) of wind energy produced in the U.S. in 2013 reduced CO_2 emissions by 126.8 million short tons, the equivalent of reducing power sector emissions by more than 5 percent or taking 20 million cars off the road. These emissions savings were broadly distributed across nearly every state, accounting for the fact that wind energy is widely deployed and that many utilities in states without wind plants are purchasing wind energy from other states. Emissions savings are reported in the states where the AVERT model indicates fossil-fired power plants

[7] EPA recently released a new tool, AVERT, that allows for the calculation of emissions reductions associated with wind energy and other non-emitting solutions. EPA's AVERT tool uses empirical power system data to identify the power plants that are most likely to have their fuel use and emissions reduced by the addition of wind energy or another zero-carbon solution, and then reports in highly granular detail the impact of that solution on each power plant's emissions. AVERT is available for download at http://epa.gov/statelocalclimate/resources/avert/index.html. AWEA put DOE EIA 2013 state-by-state wind generation data, available at http://www.eia.gov/electricity/monthly/current_year/february2014.pdf, into the AVERT tool. For this analysis, which was intended to calculate where wind power is reducing emissions in physical reality, emissions reductions were counted in the wind-producing region for power purchase contracts that are not known to call for physical delivery of the wind generation, such as those involving renewable energy credit purchases. However, as a policy matter, AWEA is advocating that EPA allocate credit for emissions reductions to the entity purchasing the wind generation and associated environmental attributes, which would result in a different state-by-state distribution. This analysis modeled emissions savings in the receiving region only for power purchase contracts that are known to call for the physical delivery of wind generation from one AVERT region to another, such as those from wind plants in the Northwest to utilities in California and from Upper and Lower Midwest wind plants to utilities in the Southeast. Because the AVERT tool's regions are not perfectly coterminous with actual grid operating areas, particularly in the Southeast and to a lesser extent the Western U.S., to better reflect reality calculated emissions savings in the Southeast were allocated to states with utilities that have wind development or wind purchases with physical delivery of the generation. AVERT does not model Hawaii and Alaska, so those were calculated separately using EIA fuel mix and emissions data. The share of total electric sector CO_2 emissions is calculated from EIA data for 2011, the most recent year for which data is available.

are reducing their emissions due to wind generation, which in interstate power markets are not always the states in which the wind plants are located. Results are listed alphabetically by state name in the first table, and ranked by amount of carbon emission reductions in the second.

According to the results from the AVERT tool, one MWh of wind energy avoids .75 tons, or 1,500 pounds, of carbon dioxide emissions on average. A typical 2 MW wind turbine avoids around 4,000-4,500 tons of carbon emissions annually, equivalent to the annual carbon emissions of more than 700 cars.

Importantly, the AVERT analysis prepared by AWEA also demonstrates that wind energy plays an important role in reducing emissions of SO_2 and NO_x, facilitating compliance with EPA regulations limiting those pollutants. Wind energy currently reduces SO_2 emissions by nearly 347 million pounds per year and NO_x by 214 million pounds per year.

Wind energy reduces emissions because electricity produced by a wind project results in an equivalent decrease in electricity production at another power plant. Due to its low operating costs (and zero fuel cost), grid operators use wind energy to ramp down the output of the online power plants with the highest operating costs, which are typically the least efficient fossil fuel-fired power plants due to their high fuel costs. Wind energy is also occasionally used to reduce the output of hydroelectric dams, which allows the dam to store water that is used later to displace fossil generation.

As discussed in AWEA's most recent annual market report, independent power system operators have also conducted studies that identify the impact of wind generation on system-wide carbon emissions, and have concluded that wind energy displaces 0.48 to 0.81 short tons of carbon dioxide per MWh of wind generated,[8] which is consistent with the results from the AVERT analysis above. Wind's emissions savings vary somewhat by region due to variations in the fossil-fuel generation mix, primarily driven by variations in the share of time that coal versus gas provide marginal generation.

The AWEA report also calculated that in 2013 wind energy saved 36.5 billion gallons of water that would have been consumed at conventional power plants, the equivalent of roughly 116 gallons per person in the U.S. or 276 billion bottles of water, providing critical relief in drought-stricken areas.[9]

[8] AWEA U.S. Wind Industry Annual Market Report for the Year Ending 2013, available at http://www.awea.org/AMR2013
[9] Ibid.

Table 1: State-by-state analysis of wind energy's 2013 emissions reductions using EPA's AVERT tool, ***listed alphabetically by state name***

	CO2 reductions (tons)	Share of 2011 electric sector CO_2 emissions	SO2 reductions (pounds)	NOX reductions (pounds)
Alabama	479,000	0.59%	3,419,000	776,000
Alaska	115,000	3.19%	202,000	1,079,000
Arizona	437,000	0.75%	217,000	548,000
Arkansas	959,000	2.48%	2,528,000	1,843,000
California	8,117,000	16.83%	66,000	6,502,000
Colorado	6,849,000	13.81%	11,413,000	14,384,000
Connecticut	321,000	4.25%	191,000	358,000
Delaware	162,000	3.71%	216,000	145,000
Florida	88,000	0.07%	259,000	115,000
Georgia	1,497,000	1.97%	7,324,000	2,334,000
Hawaii	437,000	5.07%	2,097,000	2,490,000
Idaho	303,000	38.19%	3,000	78,000
Illinois	9,727,000	8.84%	25,665,000	9,438,000
Indiana	2,760,000	2.26%	18,038,000	5,799,000
Iowa	6,496,000	13.70%	27,682,000	14,737,000
Kansas	4,356,000	10.37%	6,666,000	8,126,000
Kentucky	804,000	0.77%	3,651,000	1,040,000
Louisiana	1,705,000	3.23%	8,003,000	2,434,000
Maine	109,000	4.53%	187,000	60,000
Maryland	841,000	3.35%	3,096,000	1,509,000
Massachusetts	635,000	3.88%	1,664,000	564,000
Michigan	1,197,000	1.65%	5,510,000	2,285,000
Minnesota	5,081,000	13.76%	7,023,000	8,640,000
Mississippi	180,000	0.71%	262,000	203,000
Missouri	6,032,000	6.52%	21,689,000	7,729,000
Montana	662,000	3.50%	2,330,000	1,756,000
Nebraska	3,225,000	10.35%	13,314,000	6,467,000
Nevada	651,000	3.91%	1,049,000	1,340,000
New Hampshire	243,000	4.27%	574,000	375,000
New Jersey	532,000	3.01%	224,000	599,000
New Mexico	130,000	0.38%	82,000	374,000
New York	1,500,000	3.87%	2,504,000	2,415,000
North Dakota	2,662,000	7.85%	6,129,000	7,882,000
Ohio	2,477,000	1.99%	16,410,000	4,037,000

Oklahoma	5,996,000	9.98%	18,215,000	15,845,000
Oregon	1,586,000	18.38%	3,214,000	1,712,000
Pennsylvania	2,736,000	2.13%	14,425,000	6,914,000
Rhode Island	150,000	3.77%	6,000	58,000
South Dakota	685,000	18.04%	5,005,000	4,006,000
Tennessee	900,000	1.98%	4,947,000	819,000
Texas	25,413,000	8.86%	68,602,000	29,397,000
Utah	2,818,000	7.08%	2,785,000	10,676,000
Vermont	12,000	66.11%	171	8,000
Virginia	25,000	0.08%	144,000	77,000
Washington	3,727,000	31.52%	1,855,000	9,989,000
West Virginia	1,220,000	1.52%	2,933,000	1,265,000
Wisconsin	5,087,000	9.96%	18,602,000	6,324,000
Wyoming	4,689,000	9.40%	6,561,000	8,873,000
Total	**126,814,000**	**5.11%**	**346,981,000**	**214,422,000**

Table 2: State-by-state analysis of wind energy's 2013 emissions reductions using EPA's AVERT tool, ***ranked by carbon emissions reductions***

State	CO2 reductions (tons)	Share of 2011 electric sector CO_2 emissions	SO2 reductions (pounds)	NOX reductions (pounds)
Texas	25,413,000	8.86%	68,602,000	29,397,000
Illinois	9,727,000	8.84%	25,665,000	9,438,000
California	8,117,000	16.83%	66,000	6,502,000
Colorado	6,849,000	13.81%	11,413,000	14,384,000
Iowa	6,496,000	13.70%	27,682,000	14,737,000
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Oklahoma	5,996,000	9.98%	18,215,000	15,845,000
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Minnesota	5,081,000	13.76%	7,023,000	8,640,000
Wyoming	4,689,000	9.40%	6,561,000	8,873,000
Kansas	4,356,000	10.37%	6,666,000	8,126,000
Washington	3,727,000	31.52%	1,855,000	9,989,000
Nebraska	3,225,000	10.35%	13,314,000	6,467,000
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Ohio	2,477,000	1.99%	16,410,000	4,037,000
Louisiana	1,705,000	3.23%	8,003,000	2,434,000

Oregon	1,586,000	18.38%	3,214,000	1,712,000
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Michigan	1,197,000	1.65%	5,510,000	2,285,000
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Mississippi	180,000	0.71%	262,000	203,000
Delaware	162,000	3.71%	216,000	145,000
Rhode Island	150,000	3.77%	6,000	58,000
New Mexico	130,000	0.38%	82,000	374,000
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Virginia	25,000	0.08%	144,000	77,000
Vermont	12,000	66.11%	171	8,000
Total	**126,814,000**	**5.11%**	**346,981,000**	**214,422,000**

Wind energy is a widely available electric generating resource.

AWEA's *U.S. Wind Industry Annual Market Report for the Year Ending 2013* finds there are 61,110 megawatts (MW) of wind energy capacity installed in 39 states and Puerto Rico (Figure 1), representing more than 46,000 operational utility-scale wind turbines. There are now 16 states with 1,000 MW or more of installed wind energy capacity.

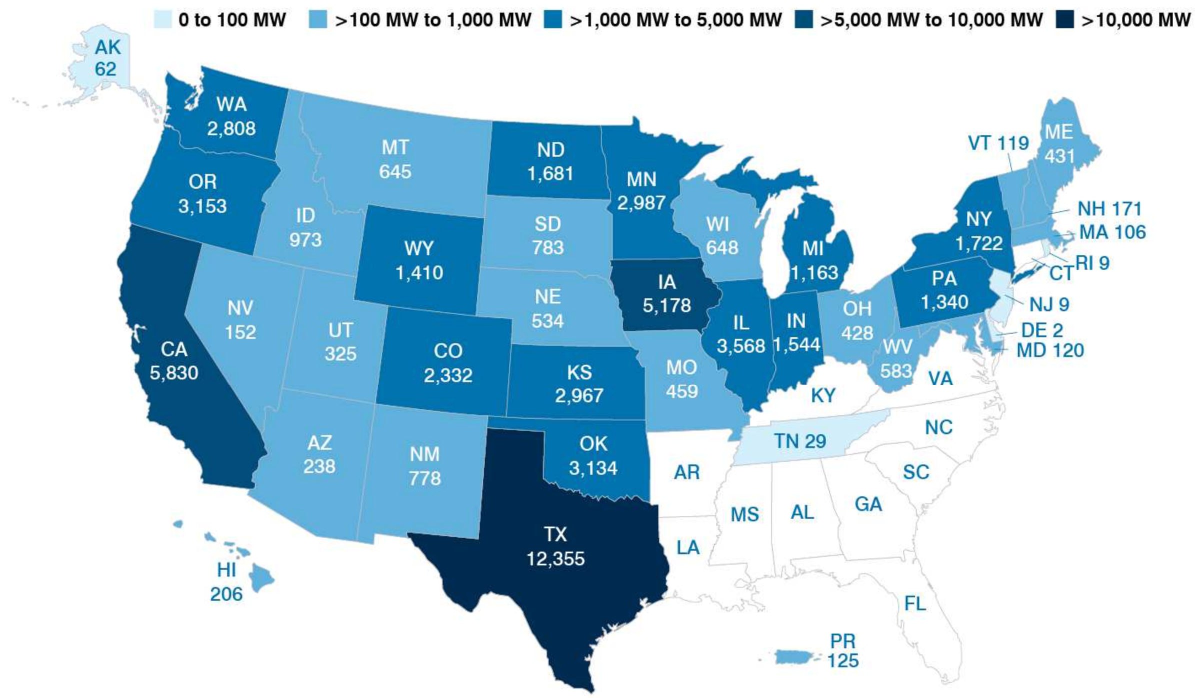

Figure 1: Installed U.S. Wind Energy Capacity in MW, by State through 2013

This represents 5.7 percent of total installed U.S. electric generating capacity. In terms of actual electricity production, wind energy accounted for 4.1 percent of electric generation in 2013 (up from 2.9 percent in 2011 and 3.5 percent in 2012). The existing wind turbine fleet provides the electrical output equivalent to 53 average coal plants, or 14 average nuclear plants.

Over the last five years, wind energy has accounted for 31 percent of all newly installed electric generating capacity, second only to natural gas. In 2012, wind energy was the largest source of all new capacity at 42 percent.

In some regions, such as the Pacific Northwest, Plains states and the Midwest, wind energy has been the primary source of new capacity over the last three years, providing 60 percent or more of all new electric generating capacity. In the Upper Midwest, wind energy provided more than 80 percent of all new generating capacity from 2011-2013.

On an average annual basis, wind energy produces more than 25 percent of the electricity in two states, 12 percent or more in nine states, and five percent or more in 17 (Figure 3).

Even the states not colored in on the two charts above increasingly have opportunities to take advantage of the environmental benefits of wind energy through both projects in-state as well as contracting for wind energy from out-of-state.

Wind energy technology is rapidly improving, mostly through the use of taller towers and longer blades that allow access to higher wind speeds and make lower-wind-speed sites more economic. As a result, wind project developers

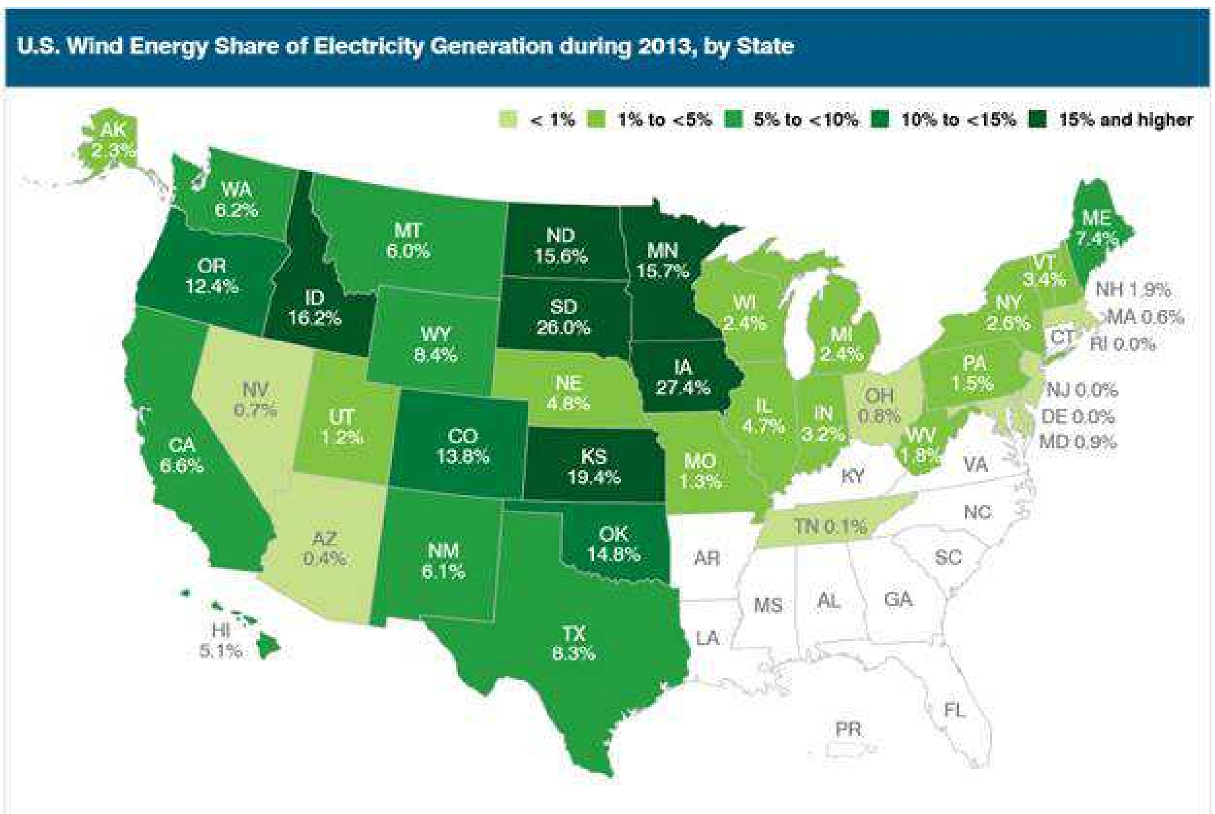

Figure 2: Percentage share of electricity generation by Wind during 2013, by State

are now exploring opportunities in states where wind energy was not previously viable, such as much of the Southeast. In addition to the 39 states with existing installed wind energy capacity, wind energy project developers have publicly acknowledged the pursuit of wind projects in Kentucky, Virginia, North Carolina, Florida, and Alabama, with initial prospecting in Georgia and Louisiana, according to press reports. Moreover, utilities in Tennessee, Arkansas, Georgia, Alabama, and Louisiana have already signed power purchase contracts to buy electricity from wind energy facilities in other states, demonstrating that wind energy is a widely available compliance option nationwide.

Wind energy is affordable.

Wind energy's costs are declining dramatically. Lazard, a widely-respected financial advisory and asset management firm reported[10] (Figure 3) in 2013 that wind energy is second only to natural gas combined cycle power plants for being the most affordable source of new electric generation, even without considering incentives. This analysis included operating, maintenance and transmission costs.

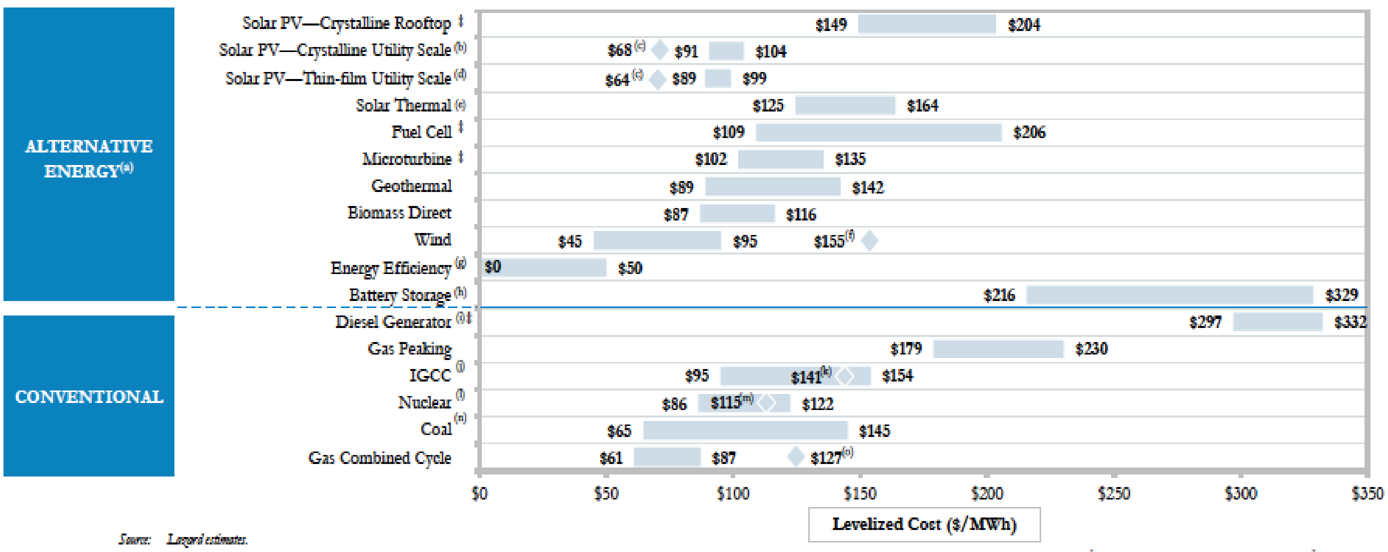

Figure 3: Levelized cost of energy (LCOE) analysis from Lazard

The U.S. Energy Information Administration projects similar results for 2019, with wind energy being one of the most affordable options second only to combined cycle natural gas.[11] Wind energy costs declined dramatically, more than 7 percent, since last year's EIA assessment.

Other DOE data confirm the marked decline in wind energy's costs, with data based on real-world contracts for wind energy showing even lower costs. DOE's annual wind market report[12] indicates the price of wind energy power purchase agreements declined 43 percent from 2009-2012 to a low of $40/MWh in 2012. Those declines appear to have continued over the last year based on recent public announcements of very low-priced wind power purchase agreements. For example, in wind-rich areas, some wind power purchase agreements have been recorded in the $20-30/MWh range.

A May 2013 report[13] by Synapse Energy Economics found that doubling the use of wind energy in the Mid-Atlantic and Great Lakes states would save consumers $6.9 billion per year on net, after accounting for all wind and transmission investment costs.

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10 Lazard's Levelized Cost of Energy Analysis, image available at http://i0.wp.com/cleantechnica.com/files/2013/09/Screen-shot-2013-09-11-at-1.50.34-PM.png. Wind's range of costs in the image are primarily due to regional variations in wind plant capacity factor and installed costs for wind. The dot at $155/MWh in the image represents offshore wind.

11 http://www.eia.gov/forecasts/aeo/electricity_generation.cfm , Table 1

12 DOE 2012 Wind Technologies Market Report, available at: http://emp.lbl.gov/sites/all/files/lbnl-6356e.pdf

13 Synapse Energy Economics, *The Net Benefit of Increased Wind Power in PJM,* by Bob Fagan, Patrick Luckow, Dr. David White, and Rachel Wilson (Cambridge, MA, 2013), available at: http://www.synapse-energy.com/Downloads/SynapseReport.2013-05.EFC.Increased-Wind-Power-in-PJM.12-062.pdf

More than a dozen other studies confirm the finding that wind energy drives electricity prices down, which is of course good for consumers.[14]

In addition to its current affordability, contracted wind energy is guaranteed to remain affordable tomorrow because it offers the stability of a long-term fixed energy price for 15-25 years. This is in contrast to the volatile prices that can characterize non-renewable fuels.[15] Wind energy keeps energy prices low much like a fixed rate mortgage protects homeowners from interest rate spikes. As the Lawrence Berkeley National Lab reported, wind energy acts as a hedge to protect consumers even in an environment in which gas prices are below historic averages.[16]

Newly released Department of Energy data[17] show that energy prices in states that use the most wind energy have on average trended lower than in states that use less wind energy. The eleven states that produce more than seven percent of their electricity from wind energy have seen their electricity prices fall by a demand-weighted average of 0.37 percent over the last 5 years, while all other states have seen their electricity prices increase by 7.79 percent over the same time period. Between the end of 2008 and the end of 2013, these eleven top wind states more than doubled their operating wind power, increasing their wind capacity by 116 percent.

Wind energy's emissions reductions are easily quantified and verified.

Wind energy's emissions reductions are readily quantifiable and verifiable, making wind energy an attractive solution for states to comply with 111(d). All utility-scale wind projects have revenue-grade metering equipment that measures the amount of wind energy production. Among other reasons, such equipment and verification is necessary to ensure compliance with power purchase contract generation requirements and for

[14] See page 4 at http://awea.files.cms-plus.com/AWEA%20White%20Paper-Consumer%20Benefits%20final.pdf

[15] The following quotes provide examples of utilities acknowledging the affordability of wind energy: "Wind Prices are extremely competitive right now, offering lower costs than other possible resources, like natural gas plants. These projects offer a great hedge against rising and often volatile fuel prices." David Sparby, president & CEO of Xcel Energy's Northern States Power announcing 600 MW of new wind power contracts on July 16, 2013, available http://www.greentechmedia.com/articles/read/wind-power-said-to-beat-natural-gas-in-midwest; an AEP subsidiary in Oklahoma tripled the amount of wind energy it planned to buy last year because "extraordinary pricing opportunities that will lower costs for PSO customers by an estimated $53 million in the first year of the contracts…annual savings are expected to grow each year over the lives of the contracts." available at: http://www.nawindpower.com/e107_plugins/content/content.php?content.12588; John Kelley, Alabama Power's Director of Forecasting and Resource Planning stated: "These agreements [referring to contracts to purchase wind power] are good for our customers for one very basic reason, and that is, they save our customers money." available at: http://www.renewableenergyworld.com/rea/news/article/2012/10/alabama-power-wants-more-affordable-wind-power; MidAmerican Energy's 2013 press release after the Iowa Utilities Board approved the addition of 1,050 MW of wind generation in Iowa "The expansion is planned to be built at no net cost to the company's customers and will help stabilize electric rates over the long term by providing a rate reduction totaling $10 million per year by 2017, commencing with a $3.3 million reduction in 2015." Available at: http://www.midamericanenergy.com/wind_news.aspx

[16] Ernest Orlando Lawrence Berkeley National Laboratory, *Revisiting the Long-Term Hedge Value of Wind Power in an Era of Low Natural Gas Prices* 21 (March 2013), available at http://emp.lbl.gov/sites/all/files/lbnl-6103e.pdf (". . . even in today's low gas price environment, and with the promise of shale gas having driven down future gas price expectations – wind power can still provide protection against many of the higher-priced natural gas scenarios . . .").

[17] U.S. Energy Information Administration, Electric Power Monthly with Data for November 2013 (January 2014), available at: http://www.eia.gov/electricity/monthly/pdf/epm.pdf. Additional analysis available in the AWEA report *Wind Power's Consumer Benefits* available at: http://awea.files.cms-plus.com/AWEA%20White%20Paper-Consumer%20Benefits%20final.pdf

purposes of claiming the federal production tax credit (PTC), which is based on electricity actually generated, on tax returns.

In addition, rigorous accounting mechanisms for renewable energy credits are in wide use in 29 states and the District of Columbia for compliance with state renewable portfolio standard requirements in those states, and accounting mechanisms are in place nationwide for verifying renewable energy production to satisfy voluntary purchases of such credits. These well-established accounting mechanisms could be readily adopted for compliance with section 111(d) to ensure that renewable energy production is not double-counted and can be precisely and rigorously quantified.

Several tools, such as marginal emissions calculations[18] and power system modeling, allow carbon emissions reductions to be calculated based on the measured wind energy production. EPA's AVERT, used for the wind emissions savings analysis above, is a free and easy-to-use option for calculating wind energy's pollution reductions.[19]

The cycling of other generation has a negligible impact on wind's emissions savings.

While other generation may on occasion need to ramp up or down to accommodate the variability of wind energy (plus the variability of other far larger sources of variability on the power system like electricity demand and the sudden failure of large conventional generators), two recent studies from different regions in the U.S. document that such cycling has virtually no negative effect on the emissions reductions from wind energy.

A peer-reviewed analysis by a Department of Energy lab found that wind energy produces 99.8 percent of the carbon emissions savings expected of a zero-emissions resource.[20] The study examined real-world hourly emissions from every power plant in the western U.S. and analyzed the impact wind energy has on the efficiency of other power plants by causing them to change their output more frequently. The study found that for a scenario with wind and solar providing 33 percent of electricity on the Western U.S. power system, one MWh of wind energy saves more than 1,190 pounds of carbon pollution on average, with those savings reduced by only 0.2 percent, or 2.4 pounds, as a result of increased cycling of fossil-fired power plants.

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[18] Marginal generation and emissions data track which power plant or power plants are economically "on the margin" in each operating hour, and thus which generating units would have been dispatched down had demand been 1 MW lower or an additional 1 MW of low-cost supply (such as from wind) been available, allowing one to calculate the marginal emissions savings based on the heat or emissions rate for those marginal units. When combined with an hourly wind output profile for the region, that allows one to calculate wind's total emissions savings with a very high degree of accuracy. Some Independent System Operators (ISOs) and utilities already calculate and publicly release data on marginal fuel mixes and emissions, and other utilities should already have the data necessary to conduct such a calculation. For example, see http://www.iso-ne.com/genrtion_resrcs/reports/emission/.

[19] Available at: http://epa.gov/statelocalclimate/resources/avert/index.html

[20] National Renewable Energy Lab Western Wind and Solar Integration Study, Phase 2 Results, available at: http://www.nrel.gov/docs/fy13osti/55588.pdf; all WWSIS documents available at: http://www.nrel.gov/electricity/transmission/western_wind.html

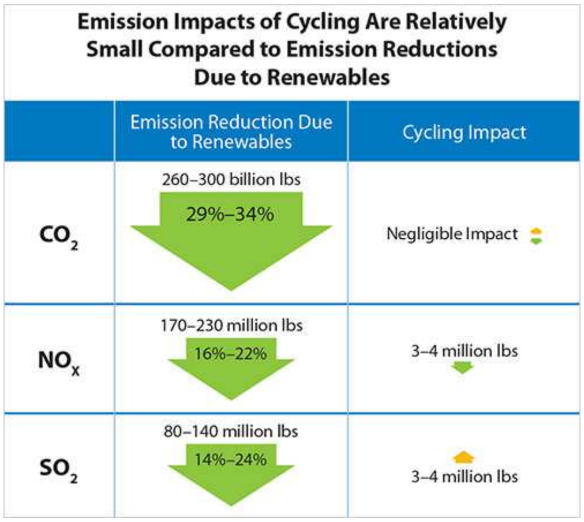

Figure 4: National Renewable Energy Lab, Western Wind and Solar Integration Study Phase II results

This finding was confirmed by PJM's March 2014 renewable integration study, which found scenarios with large amounts of wind energy still yielded the expected emissions reductions after cycling impacts were taken into account.[21]

DOE data also show that states that have ramped up their use of wind energy the most have seen the efficiency of their fossil-fired power plants hold up as well or better than states that use the least wind energy.[22]

As explained in the next section, the impact of cycling is virtually non-existent because wind energy only incrementally adds to existing power system variability and flexible reserve needs..

[21] See http://www.pjm.com/~/media/committees-groups/task-forces/irtf/postings/pjm-pris-task-3a-part-g-plant-cycling-and-emissions.ashx at page 91. The differences in CO_2 emissions savings among the study's scenarios are driven by the fact that, due to their different output profiles, onshore wind tends to offset more carbon-intensive coal generation while other renewable resources, such as offshore wind and solar, tend to offset more gas generation. The high onshore wind cases all produce emissions reductions that are almost directly proportional to the quantity of fossil MWh displaced, indicating the impact of cycling is minimal.

[22] Goggin, M., 2013, "Wind energy's emissions reductions: A statistical analysis," available at http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6672865&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel7%2F6657332%2F6672065%2F06672865.pdf%3Farnumber%3D6672865

Large amounts of wind energy can be reliably integrated onto the power system

Grid operators are now reliably accommodating very large quantities of renewable energy in the U.S. and Europe. As explained above, wind energy produces more than 25 percent of the electricity in two states, 12 percent or more in nine states, and five percent or more in 17 states on an annual basis. In certain hours, wind has supplied more than 60 percent of the electricity on the main utility system in Colorado without any reliability problems, and other grid operators have also reliably integrated very large amounts of wind energy, as indicated in Figure 6.

Grid operators in Texas have integrated more than 10,000 MW of wind energy with only very small increases in their need for flexible reserves, with the need for fast-acting flexible reserves increasing by less than 100 MW.[23] The Midcontinent Independent System Operator (MISO) has also stated that the impact of wind power has had on its need for flexible reserves, used to accommodate variability in electricity supply and demand, has been “little to none.”[24]

The March 2014 renewable integration study[25] by the PJM grid operator confirms that wind energy only minimally contributes to total power system variability, with the addition of 28,000 MW of wind capacity in the 14 percent renewable energy scenario, causing an increase in operating reserve needs of only 340 MW. This is about 1/10 of the 3,350 MW of the operating reserves PJM needs at all times to maintain

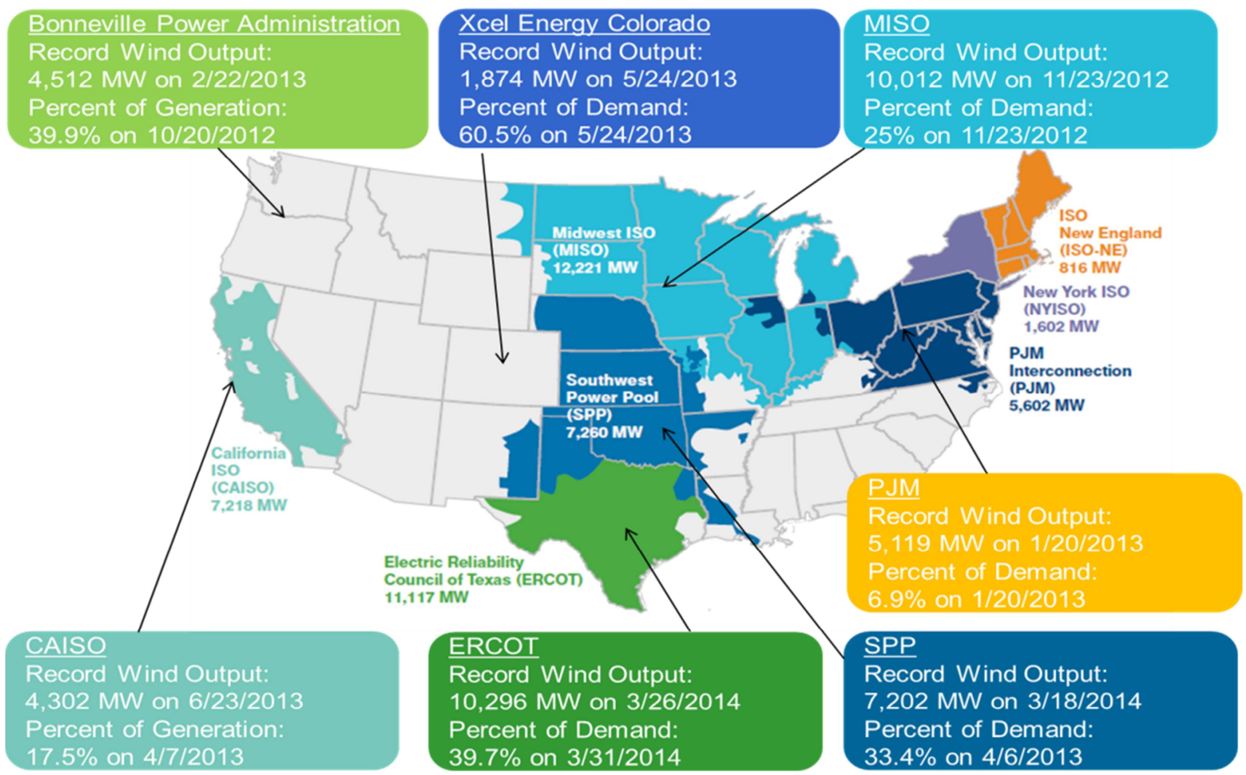

Figure 5: Wind energy integration records set in the U.S. 2012-2014; Source: AWEA Annual Market Report for the Year Ending 2013

[23] Available at: http://variablegen.org/wp-content/uploads/2012/12/Maggio-Reserve_Calculation_Methodology_Discussion.pdf
[24] Available at: http://variablegen.org/wp-content/uploads/2012/12/Navid-Reserve_Calculation.pdf
[25] Renewable Integration Study for PJM, available at: http://www.pjm.com/~/media/committees-groups/task-forces/irtf/postings/pjm-pris-final-project-review.ashx, at page 111

reliability in case a large conventional power plant abruptly fails, and less than one-third the amount of reserves necessary to deal with variability in electricity demand. Current data indicate the largest hourly changes in electricity demand are 10 times larger than the largest hourly changes in wind energy output for PJM.[26] PJM's integration study concluded that the "PJM system, with adequate transmission and ancillary services in the form of Regulation, will not have any significant issue absorbing the higher levels of renewable energy penetration considered in the study."[27]

Dozens of in-depth wind integration studies[28] confirm that far larger amounts of wind energy can be added to the power system without harming reliability. How is this possible when the wind doesn't blow all the time?

Every day, grid operators constantly accommodate variability in electricity demand and supply by increasing and decreasing the output of flexible generators – power plants like hydroelectric dams or natural gas plants can rapidly change their level of generation. Thus, the water kept behind a dam or the natural gas held in a pipeline may be thought of as a form of energy storage, with operators using this energy when it is needed and "storing" it when it is not.

Grid operators have always kept large quantities of fast-acting generation in reserve to respond to abrupt failures at large conventional power plants, a challenge and cost that is far greater than accommodating any incremental variability added by the gradual and predictable changes in the aggregate output of a wind fleet. Grid operators use these same flexible resources to accommodate any incremental variability introduced by wind energy that is not canceled out by other changes in electricity supply or demand. Wind energy's impact on total power system variability and uncertainty, and, in turn, its impact on reserve needs, is greatly reduced as most changes in wind output are offset by other changes in supply or demand.

In addition, wind plant technology has matured significantly over the last decade so that modern wind turbines provide equivalent or better capabilities[29] for supporting power system reliability needs as conventional power plants in almost every category. Recent analysis by WECC, the entity responsible for power system reliability in the Western U.S., found that in a scenario with very high renewable penetration across the West, "the system results did not identify any adverse impacts due to the lower system inertia or differently stressed paths due to the higher penetration of variable generation resources."[30] Analysis conducted for the California grid operator identified no major concerns for frequency response in a transition to a high-renewable future, finding that "None of the credible conditions examined, even cases with significantly high levels of wind and solar generation (up to 50% penetration in California), resulted in under-frequency load shedding (ULFS) or other stability problems."[31] This occurs in part because adding wind generation causes conventional power plants to have their output reduced, which provides them with more

[26] http://www.pjm.com/~/media/committees-groups/task-forces/irtf/20130417/20130417-item-05-wind-report.ashx, and http://www.pjm.com/markets-and-operations/energy/real-time/loadhryr.aspx

[27] http://www.pjm.com/~/media/committees-groups/committees/mic/20140303/20140303-pjm-pris-final-project-review.ashx, page 12

[28] For the full list, see: http://variablegen.org/resources/

[29] See this NERC report: http://www.nerc.com/docs/pc/ivgtf/IVGTF_Report_041609.pdf, at page 22

[30] Available at http://www.wecc.biz/committees/StandingCommittees/PCC/RS/RPEWG%20-%20RS%20Meetings8-21-13/Lists/Minutes/1/VGSStudy7-15-13.doc

[31] Available at http://www.caiso.com/Documents/Report-FrequencyResponseStudy.pdf

range to increase their output and provide frequency response.[32]

In addition, new techniques employing wind plants' sophisticated controls and power electronics enable wind plants themselves to provide fast-acting frequency response. The National Renewable Energy Laboratory (NREL) recently released an in-depth analysis that concluded "wind power can act in an equal or superior manner to conventional generation when providing active power control, supporting the system frequency response and improving reliability."[33] The report further documented how major utilities like Xcel Energy are using this capability of wind plants in some hours to provide all of the frequency response and regulation needed to maintain power system reliability, which has enabled Xcel's Colorado power system to at times reliably obtain more than 60 percent of its electricity from wind energy.

Going forward, the emissions reduction potential from wind energy is even greater.

More than a dozen utility and independent grid operator studies have found wind can reliably provide an even larger share of our electricity, producing even larger emissions reductions. An NREL study for the Eastern U.S.[34] found that obtaining 20 percent of electricity from wind energy cut power sector carbon emissions by 25 percent, and 30 percent wind cut carbon emissions by 37 percent, relative to the baseline generation mix.

The Department of Energy found that a scenario of 20 percent wind energy by 2030[35] was technically and economically feasible. The U.S. is currently ahead of schedule in reaching 20 percent wind energy by 2030. This DOE study found that the 20 percent wind scenario would avoid 825 million tons of CO_2 annually by 2030, cutting expected electric sector emissions by 20-25 percent, the equivalent of taking 140 million vehicles off the road. This 2008 DOE study is being updated and is expected to be released later in 2014.

Real-world experience in European countries confirms that wind energy is a reliable and highly effective tool for reducing carbon dioxide emissions. Denmark, Germany, Ireland, Portugal, and Spain lead the world in obtaining the largest share of their electricity from wind energy, and all have seen drastic declines in the carbon intensities of their electric sectors. As indicated in the table below[36], there is a very strong relationship between growth in wind generation and a decline in carbon intensity. Interestingly, Germany would have seen a far larger decline in carbon intensity had it not, for unrelated reasons, reduced the share of electricity it obtains from nuclear energy from 29.6 percent in 2001 to 17.7 percent in 2011.

Country	Wind % '01	Wind % '11	Share growth	CO_2/MWh % change
Denmark	11.9%	29.1%	17.2%	-28.9%
Germany	1.9%	8.5%	6.6%	-12.3%
Ireland	1.4%	16.6%	15.2%	-36.1%
Portugal	0.6%	17.9%	17.4%	-32.4%
Spain	3.0%	15.2%	12.2%	-23.8%
OECD Europe	**0.8%**	**5.3%**	**4.4%**	**-11.0%**

[32] http://web.mit.edu/windenergy/windweek/Presentations/GE%20Impact%20of%20Frequency%20Responsive%20Wind%20Plant%20Controls%20Pres%20and%20Paper.pdf
[33] Available at http://www.nrel.gov/news/press/2014/7301.html
[34] National Renewable Energy Lab Eastern Wind Integration Study, available at: http://www.nrel.gov/electricity/transmission/eastern_renewable.html
[35] 20% Wind Energy by 2030: Increasing Wind Energy's Contributions to U.S. Electricity Supply, U.S. Department of Energy, available at: http://www.nrel.gov/docs/fy08osti/41869.pdf
[36] The data to create this chart came from International Energy Agency statistics through 2011, the most recent year for which data on CO_2 per MWh are available. IEA statistics are available at: http://www.iea.org/statistics/

Wind energy is scalable and rapidly deployable, and thus ideal as an emissions reduction tool.

Wind plants offer a rapidly deployable solution for reducing emissions of carbon dioxide and other pollutants. Wind developers already have a large backlog of wind projects in the development pipeline, and it is typically possible to build a wind project in a little over a year, far faster than many other low- or zero-carbon solutions.

Since the end of 2005, the U.S. wind energy industry has doubled its installed capacity, on average, every 36 months. Over the last decade, the industry has gone from a low mark of installing 396 MW in 2004 to a high of more than 13,000 MW in 2012, and there are currently more wind projects under construction in the U.S. than at any point in history. U.S. wind energy's five year average annual growth rate is 19.5 percent from 2009-2013. The previously mentioned DOE 20 percent wind report found that with existing technology, the industry can ramp up to sustained deployment of around 16,000 MW of newly installed wind capacity per year.

In 2003, wind energy generated only 11 million MWh, or 0.3 percent of the generation mix. By 2008, wind energy generated 55 million MWh, or 1.3 percent of the mix. In 2013, wind energy generated 167 million MWh, or 4.1 percent of total generation.[37]

[37] The statistics in this section come for the AWEA annual market report for the year ending 2013.

Wind Power for a Cleaner America

Reducing Global Warming Pollution, Cutting Air Pollution and Saving Water

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Executive Summary

Coal- and natural gas-fired power plants pollute our air, are major contributors to global warming, and consume vast amounts of water—harming our rivers and lakes and leaving less water for other uses. Wind energy has none of these problems. It produces no air pollution, makes no contribution to global warming, and uses no water.

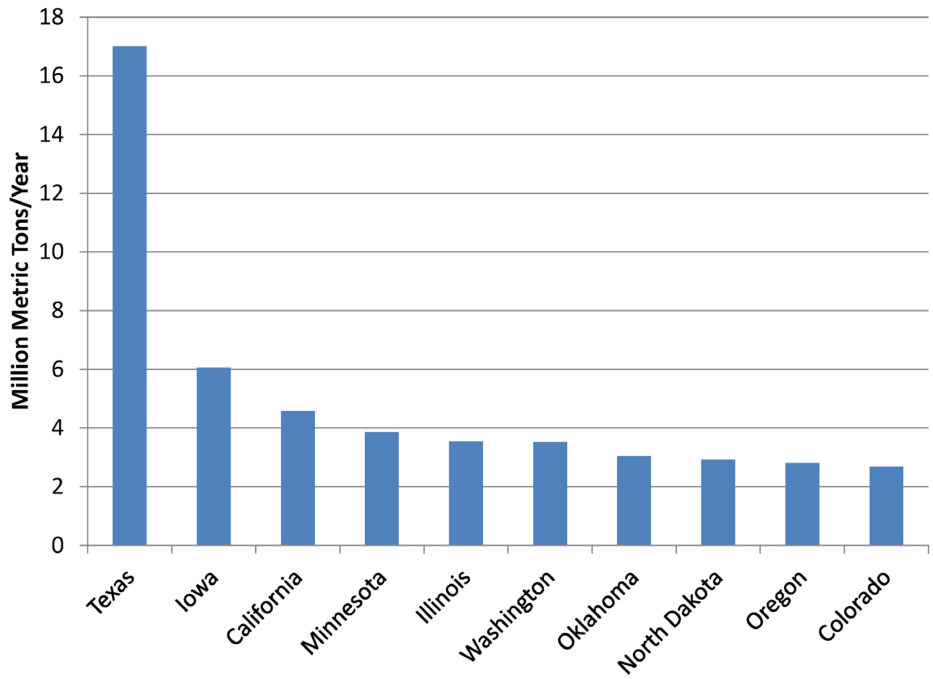
America has more than doubled its use of wind power since the beginning of 2008 and we are starting to reap the environmental rewards. **Wind energy now displaces about 68 million metric tons of global warming pollution each year—as much as is produced by 13 million cars. And wind energy now saves more than enough water nationwide to meet the needs of a city the size of Boston.**

There is still plenty of room for growth in wind energy. But the pending expiration of the production tax credit threatens the future expansion of wind power. To protect the environment, federal and state governments should continue and expand policies that support wind energy.

Burning fossil fuels for electricity generation has widespread environmental and public health consequences.

- Combustion of coal and natural gas exacerbates global warming, the effects of which are already being felt across the nation. The average annual temperature in the U.S. has already risen 2° F in the past 50 years, and the number of heat waves has increased. Extreme rain and snowfall events have become 30 percent more common. Sea

Figure ES-1. Top 10 States for Global Warming Emission Reductions from Wind Energy in 2011



level has risen eight inches or more along parts of our coasts.

- Coal- and natural gas-fired power plants require vast amounts of water for cooling, reducing the amount of water available for irrigation, wildlife, recreation or domestic use, now and in the future. More water is withdrawn from U.S. lakes, rivers, streams and aquifers for the purpose of cooling power plants than for any other purpose.
- Air pollution from power plants threatens the health of millions of Americans.

Wind energy avoids about 68 million metric tons of global warming pollution annually—equivalent to taking 13 million of today's passenger vehicles off the road—and saves more than enough water to supply the annual water needs of a city the size of Boston. Wind energy also avoids 137,000 tons of nitrogen oxide emissions and 91,000 tons of sulfur dioxide emissions, important contributors to ozone smog and soot pollution.

- Texas, Iowa and California lead the nation in wind energy capacity, delivering the greatest reductions in global warming pollution, water consumption, and health-threatening air pollution. (See Figure ES-1 and appendices.)

If construction of new wind energy projects continues from 2013 to 2016 at a pace comparable to that of recent years, the United States could reduce global warming pollution by an additional 56 million metric tons in 2016—equivalent to the amount produced by 11 million passenger vehicles. These projects would also save enough water to meet the annual water needs of 600,000 people, and reduce air pollution by an additional 108,000 tons of nitrogen oxides and 79,000 tons of sulfur dioxide.

America has abundant wind energy potential. The U.S. Department of Energy estimates that 20 percent of the nation's electricity could be supplied by wind power in 2030, up from 3 percent in 2011. To achieve that level of generation, construction of new generating capacity would need continue at levels comparable to that of recent years.

Wind energy's success in reducing air pollution and saving water will continue to grow if policies such as tax incentives and renewable electricity standards are continued and expanded at the state and federal level:

- **The production tax credit.** The federal renewable electricity production tax credit (PTC) has been one of the most important tools to help grow the wind industry in the United States, but it is set to expire at the end of 2012. The loss of the tax credit could cause new construction to drop by 75 percent—and allow global warming pollution and water consumption to continue unabated.
- **The offshore wind investment tax credit.** The offshore wind investment tax credit (ITC) is designed to address the longer timelines for development and construction of offshore wind energy facilities. It covers up to 30 percent of the cost of new wind investments and grants offshore wind developers eligibility for the credit at the point that construction begins. The offshore wind ITC also expires on December 31, 2012.
- **Strong renewable electricity standards.** A strong renewable electricity standard (RES) helps support wind energy development by requiring utilities to obtain a percentage of the electricity they provide to consumers from renewable sources. These standards help ensure that wind energy producers have a market for the electricity they generate and protect consumers from the sharp swings in energy prices that accompany over-reliance on fossil fuels. Today, 29 states have renewable electricity standards—other states and the federal government should follow their lead.
- **Tax policies for renewable energy.** Changes to the federal tax code could make more private investment available to wind energy nationwide by expanding two tax provisions that have benefited investors in non-renewable sources for decades.
- **Transmission policies.** Upgrading and expanding existing electricity transmission infrastructure can connect areas with high electricity demand to areas of high wind energy output. Transmission upgrades should occur only where clearly necessary and where environmental impacts will be minimal.

Introduction

There is a clean energy revolution happening in America.

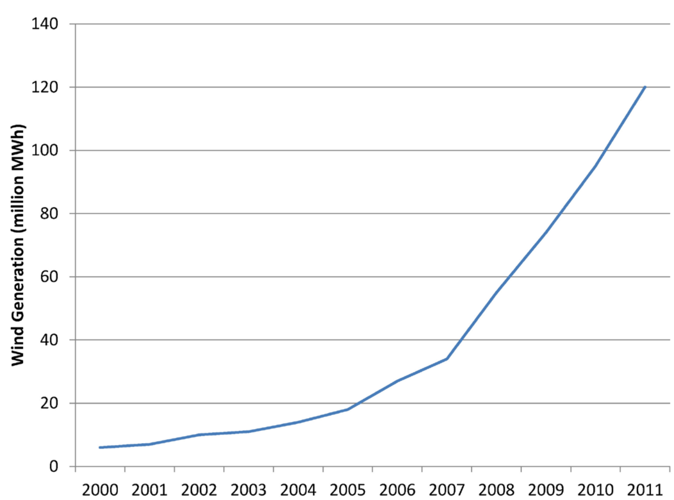
From the Pacific Coast to the Great Plains to the Northeast, renewable energy is on the rise, producing an increasing share of our electricity with minimal impact on the environment.

Consider wind energy. Just a decade ago, wind power was a trivial part of America's energy mix. Today, wind power accounts for 3 percent of our electricity. From 2006 to 2011 the amount of electricity America gets from wind power has quadrupled.

That remarkable progress is generating real environmental results. Wind energy is reducing demand for electricity from fossil fuels such as coal and natural gas—curbing emissions that cause global warming and harm our health while minimizing the use of water for cooling.

The boom in renewable energy, however, is no accident. It has taken the leadership of far-sighted state and federal policy-makers to create the conditions under which wind energy and other forms of renewable energy can thrive. With the environmental and economic benefits of wind energy becoming ever more apparent, now is the time for our leaders to renew their commitment to key clean energy policies.

Figure 1. Growth in Electricity Generated from Wind Power[1]



Power Plants Damage the Environment

Burning coal and natural gas to generate electricity damages the environment by contributing to global warming, consuming vast quantities of water, and creating health-threatening air pollution.

Power Plants Help Fuel Global Warming

Power plants produce 40 percent of America's energy-related global warming pollution.[2] (See Figure 2.) While coal-fired power plants emit twice as much carbon dioxide as natural gas plants per unit of electricity, natural gas is far from a clean fuel.[3] Leaks during the extraction, storage and transportation of natural gas can release methane, a particularly potent global warming pollutant.[4] Recent studies suggest that those leaks may make natural gas—especially gas produced through hydraulic fracturing—nearly as damaging to the climate as coal.[5]

The United States is already feeling the impacts of global warming. In the last 50 years the U.S. average annual temperature has risen 2° F and experts project that it will continue rising. By 2100, the United States Global Change Research Program (USGCRP) anticipates a temperature increase of 4 to 11° F, depending on the scale of greenhouse gas emissions.[7]

Global warming has been linked to an increase in the frequency of intense rain and snowstorms across the United States. Extreme downpours now happen 30 percent more often nationwide than in 1948, and the largest annual storms now produce 10 percent more precipitation on average.[8] Meanwhile, the number of heat waves in the United States has increased since 1960 while the projected time between prolonged dry spells has become shorter.[9]

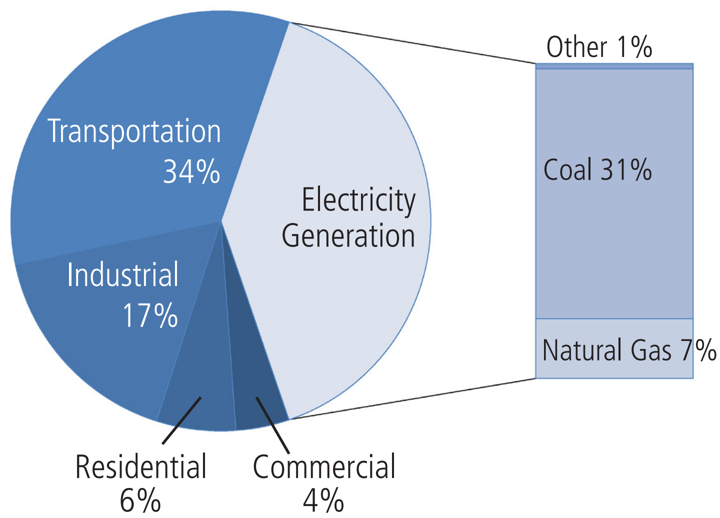
Sea levels have risen eight inches along some parts of the U.S. coastline in the past 50 years. Rising seas erode shorelines—putting homes, businesses and infrastructure at risk—and can cause saltwater intrusion into coastal fresh water aquifers, leaving some unusable without desalination.[10]

These and other impacts are expected to become more pronounced in the decades to come. Public health could suffer as heat waves become more frequent, longer lasting, and more intense, causing more heat-related deaths. Air quality will also be compromised as higher temperatures contribute to ozone "smog" formation, causing more illness, missed days of work and school, and hospitalizations.[11]

Rising temperatures may cause larger and more frequent forest fires, push some tree species northward and to higher altitudes, and eliminate other species altogether. In the oceans, warmer temperatures will cause shifts in marine species. Lobster catches in the southern part of the Northeast have already declined sharply due to the rise of a temperature-sensitive bacterial shell disease.[12]

Science tells us that we need to reduce our emissions of global warming pollution immediately and dramatically if we are to prevent the worst impacts of global warming.[13] Replacing fossil fuel-fired power plants with those using clean renewable energy is an important piece of any strategy to reduce global warming pollution.

Figure 2. Energy-Related Carbon Dioxide Emissions by Sector in the U.S., 2011, with Electricity Generation Broken Down by Fuel[6]



Power Plants Consume Lots of Water

More water is withdrawn from U.S. lakes, rivers, streams and aquifers for the purpose of cooling power plants than for any other purpose.[14] Power plants draw water from local sources for cooling, then either release the heated water back into waterways or evaporate it in a cooling tower. Consumption of water by power plants threatens critical ecosystems and reduces the amount available for human use and the protection of wildlife.

Power plants' thirst for water adds to the strain on local water supplies at times and in places where water is scarce. In Georgia in 2007, for example, a severe drought caused fierce competition for water from Lake Lanier, a major drinking water reservoir for Atlanta.[15] Georgia residents needed the water in the lake for domestic use, while a coal-fired power plant in Florida wanted more water released for cooling. At the same time, two endangered species of mussels downstream also required an adequate water flow.

Power plants in arid regions also contribute to the long-term drawdown of critical groundwater supplies. In the Southwest and California, approximately one-third to two-thirds of the water consumed by power plants comes from groundwater.[16] For many of these regions, water withdrawn for electricity generation—combined with water pumped for other purposes—has been causing water levels in aquifers to drop, threatening the long-term viability of those aquifers.

By lowering water levels in rivers and streams and raising water temperatures, power plants also threaten aquatic ecosystems. Water discharged from a power plant can be 17 degrees hotter than it was when it was withdrawn for cooling.[17] Discharge temperatures may exceed 90 degrees. This hotter water affects the health and viability of the plants and animals living in the receiving waterway. In addition to the threat posed by heat stress, warmer water holds less dissolved oxygen. For example, fish in Lake Norman, in North Carolina, have been killed by hot water discharged from the cooling systems of two power plants and low dissolved oxygen levels caused in part by the heat.[18] Low water levels due to drought and power plant withdrawals compound the problem, allowing water temperatures to rise faster and higher.

Long before fuel is burned in a power plant, the mining and extraction of coal and natural gas hurts water supplies. Natural gas extraction through hydraulic fracturing involves mixing large volumes of water with chemicals and sand. Most of the water is pumped deep underground and is lost to the water cycle forever. The little that returns to the surface usually is too polluted for any use other than more mining or fracking. Coal production, too, destroys water supplies through pollution and destruction of waterways.

When Water Runs Low, Less Electricity May Be Produced

The dependence of most coal and natural gas-fired power plants on water supplies is not just an environmental problem—it can also threaten the stability of the electric grid. Without sufficient access to cool water, power plants have to reduce their output, often at the times when their electricity is in highest demand.

In 2007, drought and high water temperatures forced Duke Energy to curtail generation at two coal-fired power plants in North Carolina.[19] During the Texas drought in 2011, the cooling water supply serving the Martin Creek Power Plant dropped so much that water had to be piped in from a nearby river to cool the plant.[20] Officials in Texas warned that if the 2011 drought continued unabated into 2012, more power plants would be affected.[21] Thus, during hot summer months—when demand for power to run air conditioners is at its highest—power plants dependent on water for cooling can be forced offline.

Power Plants Create Air Pollution

Coal- and natural gas-fired power plants also produce pollution that contributes to ozone smog, particulate matter and acid rain. This pollution hurts public health and ecosystems.

When inhaled, ozone quickly reacts with airway tissues and produces inflammation similar to sunburn on the inside of the lungs. This inflammation makes lung tissues less elastic, more sensitive to allergens, and less able to ward off infections.[22] Minor exposure to ozone can cause coughing, wheezing and throat irritation. Constant exposure to ozone over time can permanently damage lung tissues, decrease the ability to breathe normally, and exacerbate or potentially even cause chronic diseases like asthma.[23] Children, adults who are active outdoors, and people with existing respiratory system ailments suffer most from ozone's effects.

Particulate matter pollution also contributes to a host of respiratory and cardiovascular ailments. Sulfur dioxide, too, is a respiratory irritant for sensitive populations.[24] In addition, it is a major component of acid rain that has damaged forests across the eastern U.S.[25]

Wind Energy Reduces Pollution and Saves Water

Wind energy is delivering substantial reductions in global warming pollution and water consumption across the U.S. Maintaining and expanding America's commitment to wind energy will produce even greater benefits.

Benefits from Existing Wind Facilities

Wind power is delivering environmental benefits across the nation by displacing generation from coal and gas plants. In 2011, the United States generated 120 million megawatt-hours (MWh) of electricity from wind power, or nearly 3 percent of electricity generated in the U.S.[26] (See Appendix A for a breakdown of wind power generation by state.)

Assuming that wind energy displaced generation from natural gas and coal-fired power plants, the environmental benefits of wind power in 2011 included:

- Avoided emissions of 68 million metric tons of carbon dioxide—as much as would have been emitted by 13 million passenger vehicles in a year (see Appendix B).
- Water savings of 26 billion gallons, more than enough to meet the annual domestic use needs of a city the size of Boston (see Appendix C).
- Reductions in air pollution, including reductions of 137,000 pounds of nitrogen oxide emissions and 91,000

pounds of sulfur dioxide emissions (see Appendix D).

Texas reaps greater savings from wind than any other state, avoiding 17 million metric tons of carbon dioxide emissions annually, or nearly 8 percent of 2009 emissions from the state's electric sector.[27] (See Figure 3 and Table 1 on p. 15.) In addition, as the state recovers from the extreme drought in 2011 that caused major rivers to run dry, wind power is averting the consumption of 6.5 billion gallons of water per year, enough to supply all the residents of Waco.

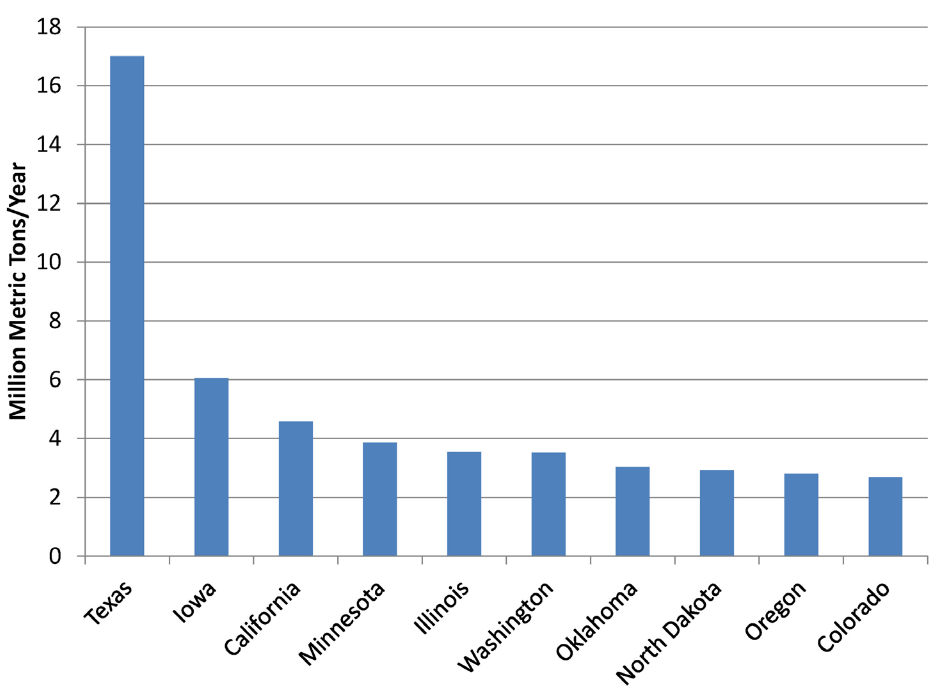
Seven of the top ten wind power-producing states are also on the list of states suffering from areas of extreme or exceptional drought in 2012.[28] Not including any new wind projects that were completed in 2012, wind power will have helped these seven states avoid consumption of 14.7 billion gallons of water at power plants, enough to serve more than 400,000 people.

The total benefits in 2012 will be greater as projects currently under construction are completed. Projects in progress could save an additional 17 million metric tons of carbon dioxide emissions per year, or as much as is emitted by 3.3 million passenger vehicles in a year. The nation can also expect to save an additional 6.5 billion gallons of water, enough for more than 175,000 people. (See appendices for full details.)

America Stands to Benefit Further if We Continue to Expand Wind Power

If construction of new wind capacity continues at a similar pace in coming years, environmental benefits will add up quickly.

Figure 3. Top 10 States for Carbon Dioxide Emission Reductions from Wind-Powered Generation in 2011



Assuming that the construction patterns observed in recent years continue, an additional 99 million MWh of electricity could be produced from wind in 2016. That would bring total generation from wind power to 249 million MWh in 2016, or 6 percent of all electricity generated in the U.S. in 2011.

Under this scenario, global warming pollution would be reduced by an additional 56 million metric tons. That is as much pollution as is released by 11 million passenger vehicles. Water savings would increase, too, with the addition of 21.6 billion gallons of savings, or enough for more than 600,000 people. This additional amount of water saved from wind energy would be almost enough to serve a city the size of Denver. Air pollution would decline by an additional 108,000 tons of nitrogen oxides and 79,000 tons of sulfur dioxide.

The U.S. has vast untapped potential wind energy. The U.S. Department of Energy estimates that 20 percent of the nation's electricity could be supplied by wind power in 2030, up from 3 percent in 2011.[29] That level of wind power could reduce electric sector water consumption by 17 percent in 2030 and cut global warming emissions by 825 million metric tons.

Table 1. Benefits of Wind Energy in Top 10 States, 2011

State	Wind Energy Production (MWh/year)	Avoided Carbon Dioxide Emissions (metric tons/year)	Water Saved (billion gallons/year)
Texas	30,051,000	17,005,000	6.54
Iowa	10,700,000	6,055,000	2.33
California	8,084,000	4,575,000	1.76
Minnesota	6,826,000	3,863,000	1.49
Illinois	6,263,000	3,544,000	1.36
Washington	6,209,000	3,514,000	1.35
Oklahoma	5,369,000	3,038,000	1.17
North Dakota	5,150,000	2,914,000	1.12
Oregon	4,961,000	2,807,000	1.08
Colorado	4,729,000	2,676,000	1.03

Table 2. Benefits in 2016 from Wind Energy Built in Top 10 States, 2013-2016, if Current Trends Continue

State	Possible New Wind Energy (MWh/year)	Avoided Carbon Dioxide Emissions (metric tons/year)	Water Saved (billion gallons/year)
Texas	20,645,000	11,683,000	4.49
Iowa	9,436,000	5,340,000	2.05
California	8,332,000	4,715,000	1.81
Oklahoma	5,761,000	3,260,000	1.25
Minnesota	5,487,000	3,105,000	1.19
Illinois	5,466,000	3,093,000	1.19
Oregon	5,012,000	2,836,000	1.09
Kansas	4,989,000	2,823,000	1.09
Washington	4,623,000	2,616,000	1.01
Colorado	4,116,000	2,329,000	0.90

America Should Continue to Invest in Wind Energy

America's clean energy boom is no accident—it is the direct result of strong, forward-thinking policies adopted over the last decade at both the state and federal levels.

As wind energy and other forms of clean, renewable energy take root in the United States—delivering ample benefits for our environment and economy—now is not the time to turn our back on further progress. To further reduce global warming pollution, curb smog and soot, move away from fossil fuels, save water, and grow our economy, the United States should continue and expand its commitment to renewable energy.

Federal Tax Incentives

Two of the most important tools that have helped grow the wind industry in the United States are the federal renewable electricity production tax credit (PTC) and the offshore wind investment tax credit (ITC).

The PTC provides a 2.2 cents per kilowatt-hour (kWh) income tax credit for utility-scale wind energy producers, helping them compete effectively with other sources of electricity by guaranteeing low electricity prices for consumers. It is available for electricity generated during the first 10 years of the wind farm's operation. The PTC is set to expire on December 31, 2012.[30]

The offshore wind investment tax credit (ITC) is designed to address the longer timelines for development and construction of offshore wind energy facilities. It covers up to 30 percent of the cost of new wind investments and grants offshore wind developers eligibility for the credit at the point that construction begins. This is important for offshore wind because of the longer timelines for development. The offshore wind ITC also expires on December 31, 2012.[31]

Policies such as the PTC and ITC recognize that renewable energy is a key component of an electricity grid that is not only cleaner but that also delivers stable, reasonable prices for consumers. Renewable energy sources such as wind are not subject to the volatility of coal and natural gas prices, and can deliver reliable, affordable electricity for decades, making them a smart long-term investment in the nation's energy future.

Over the past 13 years, the PTC has been only sporadically available. When the PTC has been renewed by Congress for only for one or two years at a time or even allowed to expire, the environment of economic uncertainty has discouraged wind developers from building new capacity, stunting industry growth. For instance, in 2000, 2002 and 2004—years when the PTC was allowed to expire temporarily—new wind installations dropped by 93 percent, 73 percent and 77 percent, respectively, from the previous year when the PTC had been in force.[32]

The loss of the PTC could cause new construction to fall by 75 percent.[33] Failing to extend the PTC beyond 2012 could result in the loss of $10 billion in investment and 37,000 jobs in 2013, according to an analysis by Navigant Consulting for the American Wind Energy Association.[34] Opponents of tax credits like the PTC and ITC argue that they are too expensive, costing taxpayers billions of dollars per year.[35]

Strong Renewable Electricity Standards

A renewable electricity standard (RES) helps support wind energy development by requiring utilities to obtain a percentage of the electricity they provide to consumers from renewable sources. These standards help ensure that wind energy producers have a market for the electricity they generate, as electricity suppliers seek to reach their required threshold for renewable electricity. This certainty makes it easier for wind developers to finance and build new wind power installations. Today, 29 states have renewable electricity standards.[36] Some of the states with the strongest standards, such as Colorado, have seen the greatest growth in wind power generation. Raising the goals of existing state-level renewable electricity standards and adopting a national renewable electricity standard would further promote construction of wind capacity.

Transmission Infrastructure

Policymakers should prioritize upgrading and expanding existing electricity transmission infrastructure to connect areas with high electricity demand to areas of high wind energy output. Old and inefficient transmission infrastructure is one of the largest impediments to integrating more wind energy into the grid. Transmission upgrades should occur only where clearly necessary and where environmental impacts will be minimal.

Offshore Wind Resources

Some of the best wind energy resources are offshore. To capture that potential, policymakers need to set a bold goal for offshore wind development in the Atlantic. A goal will help articulate the important role of offshore wind in America's energy future. The Department of the Interior and the Bureau of Ocean Energy Management will need sufficient staff and resources to manage multiple renewable energy leases along the coast and to promote an efficient leasing process. A coordinated effort by federal, state and regional economic development, energy and commerce agencies is needed to develop commitments to purchase offshore wind power. Finally, offshore wind projects must be sited, constructed and operated responsibly in order to avoid and mitigate conflict with local marine life and other uses.

Methodology

We obtained data on annual wind generation (in MWh) in 2011 from Energy Information Administration, *Electric Power Monthly*, February 2012.

To estimate output from wind facilities currently under construction, we obtained data on wind capacity (in MW) under construction from American Wind Energy Association (AWEA), *Wind Energy Facts* (factsheets), August 2012. We assume that the capacity factor of wind farms varies by region, shown in Table A-1, per Ryan Wiser and Mark Bolinger, *2011 Wind Technologies Market Report*, U.S. Department of Energy, August 2012. Because the state-level data did not include Alaska or Hawaii, we assumed wind projects in those states achieved the national average capacity factor of 33 percent. We assumed that the southeastern states, which have wind resources similar to the eastern region, have the same capacity factor as the East.

Our estimate of future wind energy construction is based on a national projection of an additional 34 GW of capacity from 2013 through 2016 in Navigant Consulting, for the American Wind Energy Association, *Impact of the Production Tax Credit on the U.S. Wind Market*, 12 December 2011.

Table A-1. Average Capacity Factor, Based on Projects Built from 2004-2010[37]

Region	Average Capacity Factor
East	25%
New England	28%
California	30%
Great Lakes	31%
Northwest	32%
Texas	34%
Mountain	36%
Heartland	37%

We apportioned this out to the states according to their share of the nation's existing and under-construction wind power capacity in MW, per AWEA, *Wind Energy Facts* (factsheets), August 2012. (Note that this produces results that appear to be at odds with the sum of output from existing and under-construction facilities. Some states have installed capacity (MW) that produced relatively little output (MWh) in 2011, but which was factored into future capacity and output.) We translated this future wind capacity into megawatt-hours (MWh) of generation following the same method as for facilities currently under construction, described above.

Estimating Carbon Dioxide Emission Reductions

When a wind turbine generates electricity, it displaces some other source of electricity on the grid. In the short run, this means that production at another power plant is reduced; in the longer run, it means that fewer fossil fuel-fired plants are built. In our calculations, we assume that 75 percent of the time, the power generator that is no longer producing electricity is a natural gas-powered plant and 25 percent of the time the facility is coal fired. Typically, in practice, the plant that is turned off is that with the highest marginal cost of production.

The fuel used in the marginal plant varies from region to region and from time to time based on a particular region's generating mix and prices. In the PJM generating region, which stretches from Maryland to New Jersey to Illinois, wind historically has displaced coal 60 percent of the time and natural gas and oil the rest of the time.[38] In contrast, in California and the Pacific Northwest, where a much smaller portion of electricity is generated by coal, natural gas is far more often the marginal fuel.

A ratio of 75 percent natural gas and 25 percent coal displacement is broadly representative of how wind influences the electricity grid. We obtained a national average emissions rate for coal and natural gas plants from Environmental Protection Agency, *eGRID2012 Version 1.0 Year 2009 GHG Annual Output Emission Rates*, 10 May 2012.

To put carbon dioxide emission reductions in perspective, we calculated how many passenger vehicles would have to be removed from the road in order to produce comparable savings. Data on vehicle emissions rates is from Environmental Protection Agency, *Greenhouse Gas Equivalencies Calculator*, May 2011.

Estimating Water Consumption Avoided

We estimated water savings using freshwater and saltwater consumption rates in coal, natural gas combined cycle and natural gas combustion turbine plants from U.S. Department of Energy, Office of Energy Efficiency and Renewable

Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, July 2008. We used the same assumption as for carbon dioxide savings that 75 percent of displaced generation is from natural gas and 25 percent is from coal.

We calculated how many individuals' domestic water needs could be met with this amount of saved water. We obtained state-level per capita domestic water use from Joan Kenny, et al., *Estimated Use of Water in the United States in 2005*, U.S. Geological Survey, 2009.

Estimating Avoided Emissions of Nitrogen Oxides and Sulfur Dioxide

We also estimated avoided emissions of nitrogen oxides and sulfur dioxide for each state. We calculated an average emissions rate for natural gas and coal generation in each state using 2010 nitrogen oxides and sulfur dioxide emission data from Energy Information Administration, *State Historical Tables for 2010* (EIA-767 and EIA-906), December 2011. We divided emissions by generation from natural gas and coal plants in 2010, per Energy Information Administration, *Net Generation by State by Type of Producer by Energy Source, Annual Back to 1990* (EIA-906, EIA-920 and EIA-923). We then created an average emission rate for each state based on a 25 percent coal/75 percent natural gas split.

Appendix A. Current and Future Annual Wind Generation by State

State	Rank: Existing Wind Energy	Existing Wind Energy (MWh/year)	Wind Energy Under Construction (MWh/year)	In 2016, Possible New Wind Energy (MWh/year)
Texas	1	30,051,000	4,685,000	20,645,000
Iowa	2	10,700,000	1,974,000	9,436,000
California	3	8,084,000	3,062,000	8,332,000
Minnesota	4	6,826,000	865,000	5,487,000
Illinois	5	6,263,000	1,342,000	5,466,000
Washington	6	6,209,000	586,000	4,623,000
Oklahoma	7	5,369,000	3,121,000	5,761,000
North Dakota	8	5,150,000	681,000	3,087,000
Oregon	9	4,961,000	932,000	5,012,000
Colorado	10	4,729,000	1,564,000	4,116,000
Wyoming	11	4,709,000	0	2,526,000
Kansas	12	3,759,000	4,243,000	4,989,000
Indiana	13	3,289,000	546,000	2,377,000
New York	14	2,826,000	473,000	2,030,000
South Dakota	15	2,692,000	0	1,441,000
New Mexico	16	2,089,000	85,000	1,390,000
Pennsylvania	17	1,968,000	940,000	1,663,000
Idaho	18	1,308,000	883,000	1,483,000
Montana	19	1,243,000	642,000	992,000
Wisconsin	20	1,196,000	0	972,000
Missouri	21	1,179,000	0	844,000
West Virginia	22	1,099,000	0	724,000
Nebraska	23	1,018,000	389,000	840,000
Maine	24	713,000	75,000	536,000
Utah	25	576,000	0	581,000
Michigan	26	437,000	1,358,000	1,520,000
Hawaii	27	326,000	330,000	339,000
Maryland	28	319,000	0	149,000
Arizona	29	249,000	0	426,000
Ohio	30	175,000	5,000	648,000
New Hampshire	31	78,000	105,000	215,000
Tennessee	32	53,000	0	36,000
Vermont	33	33,000	138,000	135,000
Massachusetts	34	28,000	74,000	122,000
Alaska	35	16,000	121,000	89,000
New Jersey	36	16,000	3,000	13,000
Delaware	37 (tie)	0	0	2,000
Nevada	37 (tie)	0	483,000	274,000
Rhode Island	37 (tie)	0	10,000	9,000
Virginia	37 (tie)	0	83,000	47,000

Appendix B. Annual Carbon Dioxide Emissions Avoided by Wind Energy

	Avoided Carbon Dioxide Emissions (metric tons/year)			Vehicles Equivalent of Avoided Pollution		
State	Existing Wind Energy	Wind Energy Under Construction	In 2016, Possible New Wind Energy	Existing Wind Energy	Wind Energy Under Construction	In 2016, Possible New Wind Energy
Alaska	9,000	69,000	50,000	2,000	13,000	10,000
Arizona	141,000	0	241,000	28,000	0	47,000
California	4,575,000	1,733,000	4,715,000	897,000	340,000	925,000
Colorado	2,676,000	885,000	2,329,000	525,000	174,000	457,000
Delaware	0	0	1,000	0	0	0
Hawaii	184,000	186,000	192,000	36,000	37,000	38,000
Idaho	740,000	500,000	839,000	145,000	98,000	165,000
Illinois	3,544,000	759,000	3,093,000	695,000	149,000	607,000
Indiana	1,861,000	309,000	1,345,000	365,000	61,000	264,000
Iowa	6,055,000	1,117,000	5,340,000	1,187,000	219,000	1,047,000
Kansas	2,127,000	2,401,000	2,823,000	417,000	471,000	554,000
Maine	403,000	42,000	303,000	79,000	8,000	59,000
Maryland	181,000	0	84,000	35,000	0	17,000
Massachusetts	16,000	42,000	69,000	3,000	8,000	14,000
Michigan	247,000	768,000	860,000	48,000	151,000	169,000
Minnesota	3,863,000	490,000	3,105,000	757,000	96,000	609,000
Missouri	667,000	0	477,000	131,000	0	94,000
Montana	703,000	363,000	561,000	138,000	71,000	110,000
Nebraska	576,000	220,000	475,000	113,000	43,000	93,000
Nevada	0	273,000	155,000	0	54,000	30,000
New Hampshire	44,000	59,000	122,000	9,000	12,000	24,000
New Jersey	9,000	2,000	7,000	2,000	0	1,000
New Mexico	1,182,000	48,000	786,000	232,000	9,000	154,000
New York	1,599,000	268,000	1,149,000	314,000	52,000	225,000
North Dakota	2,914,000	385,000	1,747,000	571,000	76,000	342,000
Ohio	99,000	3,000	367,000	19,000	1,000	72,000
Oklahoma	3,038,000	1,766,000	3,260,000	596,000	346,000	639,000
Oregon	2,807,000	527,000	2,836,000	550,000	103,000	556,000
Pennsylvania	1,114,000	532,000	941,000	218,000	104,000	185,000
Rhode Island	0	6,000	5,000	0	1,000	1,000
South Dakota	1,523,000	0	816,000	299,000	0	160,000
Tennessee	30,000	0	20,000	6,000	0	4,000
Texas	17,005,000	2,651,000	11,683,000	3,334,000	520,000	2,291,000
Utah	326,000	0	329,000	64,000	0	65,000
Vermont	19,000	78,000	77,000	4,000	15,000	15,000
Virginia	0	47,000	27,000	0	9,000	5,000
Washington	3,514,000	332,000	2,616,000	689,000	65,000	513,000
West Virginia	622,000	0	410,000	122,000	0	80,000
Wisconsin	677,000	0	550,000	133,000	0	108,000
Wyoming	2,665,000	0	1,429,000	523,000	0	280,000

Appendix C. Annual Water Consumption Avoided with Wind Energy

	Water Saved (million gallons/year)			Water Saved Could Provide Domestic Water for This Many People		
State	**Existing Wind Energy**	**Wind Energy Under Construction**	**In 2016, Possible New Wind Energy**	**Existing Wind Energy**	**Wind Energy Under Construction**	**In 2016, Possible New Wind Energy**
Alaska	3	26	19	100	800	600
Arizona	54	0	93	1,100	0	1,800
California	1,759	666	1,813	38,900	14,700	40,100
Colorado	1,029	340	896	23,300	7,700	20,300
Delaware	0	0	1	0	0	0
Hawaii	71	72	74	1,200	1,200	1,200
Idaho	285	192	323	4,200	2,800	4,700
Illinois	1,363	292	1,189	41,500	8,900	36,200
Indiana	716	119	517	25,800	4,300	18,600
Iowa	2,328	430	2,053	98,100	18,100	86,500
Kansas	818	923	1,086	27,700	31,200	36,700
Maine	155	16	117	7,900	800	5,900
Maryland	69	0	32	1,700	0	800
Massachusetts	6	16	26	200	500	900
Michigan	95	295	331	3,300	10,100	11,300
Minnesota	1,485	188	1,194	59,800	7,600	48,100
Missouri	257	0	184	8,000	0	5,700
Montana	270	140	216	6,600	3,400	5,300
Nebraska	222	85	183	4,500	1,700	3,700
Nevada	0	105	60	0	1,500	900
New Hampshire	17	23	47	600	800	1,700
New Jersey	3	1	3	100	0	100
New Mexico	455	19	302	11,600	500	7,700
New York	615	103	442	17,400	2,900	12,500
North Dakota	1,121	148	672	33,700	4,500	20,200
Ohio	38	1	141	1,500	0	5,600
Oklahoma	1,168	679	1,254	37,700	21,900	40,400
Oregon	1,080	203	1,091	24,400	4,600	24,700
Pennsylvania	428	204	362	20,600	9,800	17,400
Rhode Island	0	2	2	0	100	100
South Dakota	586	0	314	17,100	0	9,100
Tennessee	12	0	8	400	0	300
Texas	6,539	1,019	4,492	130,800	20,400	89,800
Utah	125	0	126	1,800	0	1,900
Vermont	7	30	29	300	1,300	1,300
Virginia	0	18	10	0	700	400
Washington	1,351	127	1,006	35,900	3,400	26,800
West Virginia	239	0	158	6,500	0	4,300
Wisconsin	260	0	211	12,500	0	10,200
Wyoming	1,025	0	550	18,500	0	9,900

Appendix D. Annual Nitrogen Oxide and Sulfur Dioxide Emissions Avoided with Wind Energy

	Avoided NO_X Emissions (tons/year)			Avoided SO_2 Emissions (tons/year)		
State	**Existing Wind Energy**	**Wind Energy Under Construction**	**In 2016, Possible New Wind Energy**	**Existing Wind Energy**	**Wind Energy Under Construction**	**In 2016, Possible New Wind Energy**
Alaska	40	310	230	20	120	90
Arizona	100	0	180	50	0	90
California	6,110	2,310	6,300	1,730	650	1,780
Colorado	3,680	1,220	3,210	1,700	560	1,480
Delaware	0	0	0	0	0	0
Hawaii	70	70	80	70	70	80
Idaho	9,310	6,280	10,550	14,050	9,490	15,940
Illinois	3,310	710	2,890	4,270	910	3,720
Indiana	1,710	280	1,230	3,100	520	2,240
Iowa	8,480	1,560	7,480	7,420	1,370	6,540
Kansas	5,540	6,250	7,350	1,290	1,460	1,720
Maine	670	70	500	1,110	120	840
Maryland	310	0	140	160	0	70
Massachusetts	10	20	40	30	80	140
Michigan	260	820	920	420	1,310	1,470
Minnesota	5,480	690	4,400	3,480	440	2,800
Missouri	520	0	370	1,000	0	720
Montana	5,450	2,810	4,350	340	180	270
Nebraska	1,290	490	1,060	780	300	640
Nevada	0	270	160	0	140	80
New Hampshire	30	40	80	230	310	630
New Jersey	10	0	10	10	0	10
New Mexico	1,830	70	1,220	340	10	230
New York	1,420	240	1,020	2,940	490	2,110
North Carolina	0	0	0	0	0	0
North Dakota	35,050	4,630	21,010	5,750	760	3,450
Ohio	70	0	250	240	10	880
Oklahoma	4,940	2,870	5,300	3,810	2,220	4,090
Oregon	3,470	650	3,510	4,700	880	4,750
Pennsylvania	780	370	660	1,880	900	1,590
Rhode Island	0	0	0	0	0	0
South Dakota	3,530	0	1,890	2,670	0	1,430
Tennessee	30	0	20	40	0	30
Texas	16,780	2,620	11,530	22,990	3,580	15,800
Utah	390	0	390	120	0	120
Vermont	10	60	60	0	0	0
Virginia	0	50	30	0	100	50
Washington	3,850	360	2,870	600	60	450
West Virginia	640	0	420	410	0	270
Wisconsin	600	0	480	1,030	0	840
Wyoming	10,740	0	5,760	2,040	0	1,090

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Wind Energy For A Cleaner America II

Wind Energy's Growing Benefits for Our Environment and Our Health

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Executive Summary

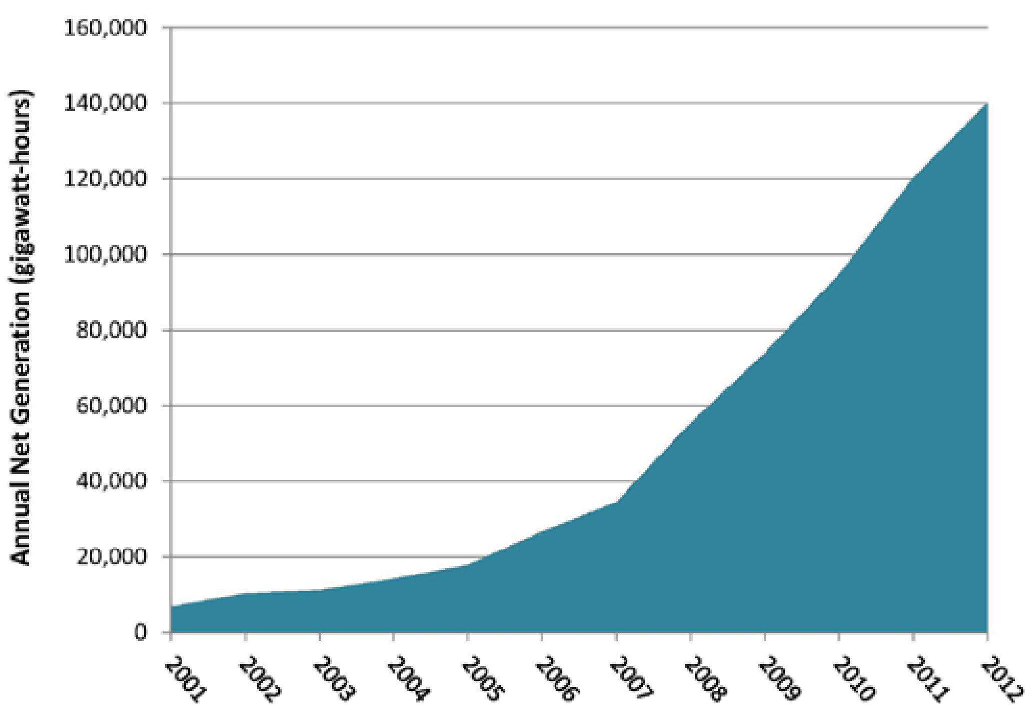
Burning fossil fuels to generate electricity pollutes our air, contributes to global warming, and consumes vast amounts of water—harming our rivers and lakes and leaving less water for other uses. In contrast, wind energy produces no air pollution, makes no contribution to global warming, and uses no water.

America's wind power capacity has quadrupled in the last five years and wind energy now generates as much electricity as is used every year in Georgia. Thanks to wind energy, America uses less water for power plants and produces less climate-altering carbon pollution.

Wind energy displaced about 84.7 million metric tons of carbon dioxide emissions in 2012—more global warming-inducing carbon dioxide pollution than is produced annually in Massachusetts, Maryland, South Carolina or Washington state. Wind energy also saves enough water nationwide to meet the domestic water needs of more than a million people.

America has vast wind energy resources, and there is still plenty of room for growth. But the pending expiration of the federal renewable energy production tax credit and investment tax credit threatens the future expansion of wind power. To protect the

Figure ES-1. Growth in Electricity Generated by Wind Power[1]



environment, federal and state governments should continue and expand policies that support wind energy.

Wind energy is on the rise in the United States.

- Electricity generated with wind power quadrupled in the last five years, from about 34,500 gigawatt-hours (GWh) in 2007 to more than 140,000 GWh at the end of 2012—or as much electricity as is used each year in Georgia. (See Figure ES-1.)
- Wind energy was the largest source of new electricity capacity added to the grid in 2012.
- Nine states now have enough wind turbines to supply 12 percent or more of their annual electricity needs in an average year, with Iowa, South Dakota and Kansas now possessing enough wind turbines to supply more than 20 percent of their annual electricity needs.

By displacing dirty electricity from fossil fuel-fired power plants, wind energy saves water and reduces pollution. In 2012, wind energy helped the United States:

- **Avoid 84.7 million metric tons of carbon dioxide pollution—or as much pollution as is produced by more than 17 million of today's passenger vehicles in a year.** Fossil fuel-fired power plants are the nation's largest source of carbon dioxide, the leading global warming pollutant. In the United States, warmer temperatures caused by global warming have already increased the frequency and severity of heat waves and heavy downpours, resulting in more intense wildfires, floods, droughts, and tropical storms and hurricanes.
- **Save enough water to supply the annual domestic water needs of more than a million people.** Power plants use water for cooling, reducing the amount of water available for irrigation, wildlife, recreation or domestic use. More water is withdrawn from U.S. lakes, rivers, streams and aquifers for the purpose of cooling power plants than for any other purpose.
- **Avoid 79,600 tons of nitrogen oxide (NO_X) and 98,400 tons of sulfur dioxide emissions.** Nitrogen oxides are a key ingredient of smog, which contributes to asthma and other respiratory problems; power plants are responsible for about 15 percent of the nation's total nitrogen oxide (NO_X) pollution each year. Power plants also produce about 60 percent of all sulfur dioxide pollution, which contributes to acid rain. Finally, coal-fired power plants emit heavy metals such as mercury, a potent neurotoxicant that can cause developmental and neurological disorders in babies and children. Nearly two-thirds of all airborne mercury pollution in the United States in 2010 came from the smokestacks of coal-fired power plants.

If America were to continue to add onshore wind capacity at the rate it did from 2007 to 2012, and take the first steps toward development of its massive potential for offshore wind, by 2018 wind energy will be delivering the following benefits:

- Averting a total of 157 million metric tons of carbon dioxide pollution annually—or more carbon dioxide pollution than was produced by Georgia, Michigan or New York in 2011.
- Saving enough water to supply the annual domestic water needs of 2.1 million people—roughly as many people as live in the city of Houston and more than live in Philadelphia, Phoenix or San Diego.
- Averting more than 121,000 tons of smog-forming nitrogen oxide pollution and 194,000 tons of sulfur dioxide pollution each year.

Wind energy's success in reducing air pollution and saving water will continue to grow if America makes a stable, long-term commitment to clean energy at the local, state and national levels. Specific policies that are essential to the development of wind energy include:

- The federal renewable energy **production tax credit** (PTC) and **investment tax credit** (ITC). The PTC provides an income tax credit of 2.3 cents per kilowatt-hour (kWh) for utility-scale wind energy producers for 10 years, while the ITC covers up to 30 percent of the capital cost of new renewable energy investments. Wind energy developers can take one of the two credits, which help reduce the financial risk of renewable energy investments and create new financing opportunities for wind energy. Both the ITC and the PTC, however, are scheduled to expire at the end of 2013.
- Strong **renewable electricity standards**. A strong renewable electricity standard (RES) helps support wind energy development by requiring utilities to obtain a percentage of the electricity they provide to consumers from renewable sources. These standards help ensure that wind energy producers have a market for the electricity they generate and protect consumers from the sharp swings in energy prices that accompany over-reliance on fossil fuels. Today, 29 states have renewable electricity standards—other states and the federal government should follow their lead.
- Continued coordination and collaboration between state and federal agencies to expedite **siting of offshore wind facilities** in areas that avoid environmental harm.

Introduction

From the Pacific Coast to the Great Plains to the Atlantic Ocean, wind power is on the rise in the United States, producing an increasing share of our electricity with minimal impact on the environment.

Just a decade ago, wind energy was a trivial part of the nation's electricity picture. Today, wind energy is one of the fastest growing forms of electricity generation and an increasingly important part of the nation's energy mix.

The remarkable progress of wind energy is generating real environmental results. Wind energy is reducing demand for electricity from fossil fuels such as coal and natural gas—curbing emissions that cause global warming while minimizing the use of water for cooling.

The boom in wind power is no accident, however. State and federal policy-makers have implemented far-sighted public policies that have created the conditions under which wind energy can thrive. By unleashing the energies of innovative companies and American workers, and tapping the natural power of the wind, these public policies are moving the nation toward a clean energy future and delivering growing benefits for our environment and our health.

With the environmental and economic advantages of wind energy becoming ever more apparent, now is the time for our leaders to renew their commitment to the key public policies that will enable the nation to achieve even greater benefits in the years to come.

Wind Energy Is Growing Rapidly in The U.S.

Wind energy is quickly becoming an important part of the energy mix in the United States. Nationwide, electricity generation from wind power has quadrupled in the last five years, from 34,500 GWh in 2007 to more than 140,000 GWh in 2012—or as much electricity as is used each year in the state of Georgia.[2] (See Figure 1.) Nine states now have enough wind turbines to produce 12 percent or more of their annual electricity needs in an average year—with Iowa, South Dakota and Kansas now having enough wind energy capacity to produce 20 percent or more of their annual electricity needs in a typical year.[3]

With more than 10,000 MW of new wind capacity installed in 2012, wind energy became the largest source of new electricity generating capacity in the United States last year—ahead of even natural gas, which added about 8,746 MW of new capacity.[5] In 2012, wind energy accounted for more than 40 percent of the new electric generating capacity added to the grid in the United States, making it the nation's largest source of new generating capacity.[6] (See Figure 2.)

Figure 1. Growth in Electricity Generated by Wind Power[4]

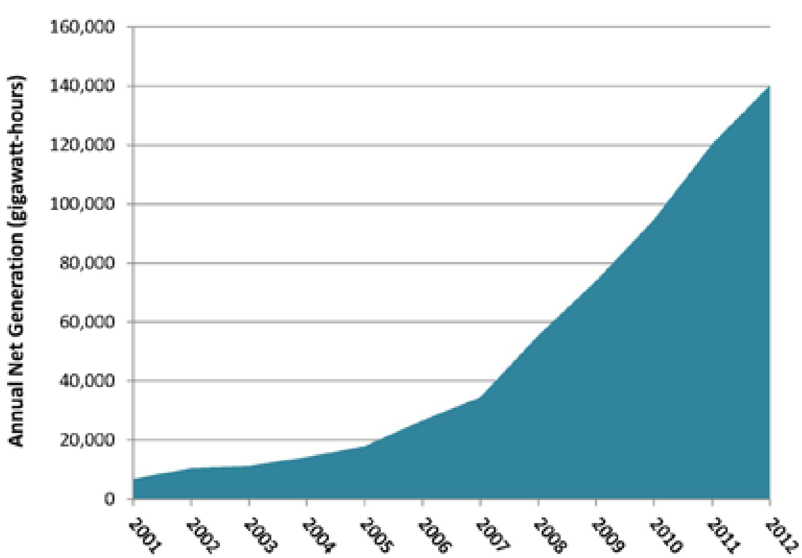
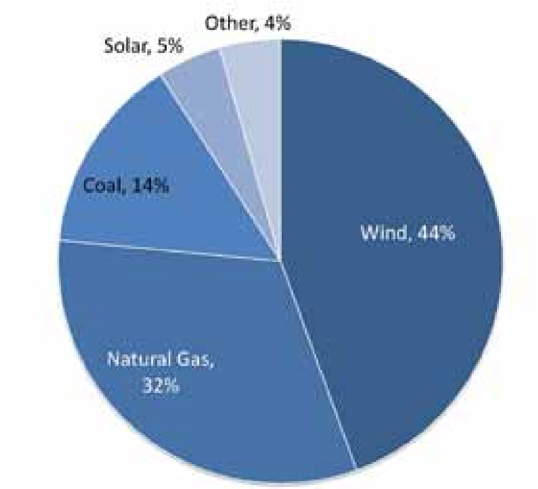


Figure 2. New Electricity Capacity Additions by Technology, 2012[7]



Employment in the wind industry has also grown significantly. In 2003, the wind industry directly employed 24,300 people.[8] By 2012, that number had more than tripled to more than 80,000 people.[9]

As the wind industry has grown and technology has advanced, the cost of wind energy has declined. By 2013, these cost declines had led wind energy to be competitive with other forms of power generation. When the costs imposed by emissions of global warming pollution are factored in, wind power is less expensive than new coal-fired power plants and is competitive with new natural gas power plants and even existing coal-fired plants.[10]

Power Plants Damage the Environment

Burning coal and natural gas to generate electricity damages the environment by contributing to global warming, consuming vast quantities of water, and creating health-threatening air pollution. Wind energy has none of these problems—it emits no air pollution and consumes little or no water. Generating clean electricity using wind power reduces the need for dirty electricity from fossil fuel-fired power plants, avoiding millions of tons of harmful air pollution and saving millions of gallons of water.

Power Plants Are America's Leading Source of Global Warming Pollution

Fossil fuel-fired power plants are the nation's largest source of carbon dioxide pollution, the leading global warming pollutant.[11] In 2011, power plants were responsible for 42 percent of all U.S. global warming pollution.[12] (See Figure 3.)

Figure 3. Energy-Related Carbon Dioxide Emissions by Sector in the U.S., 2011, with Electricity Generation Broken Down by Fuel[13]

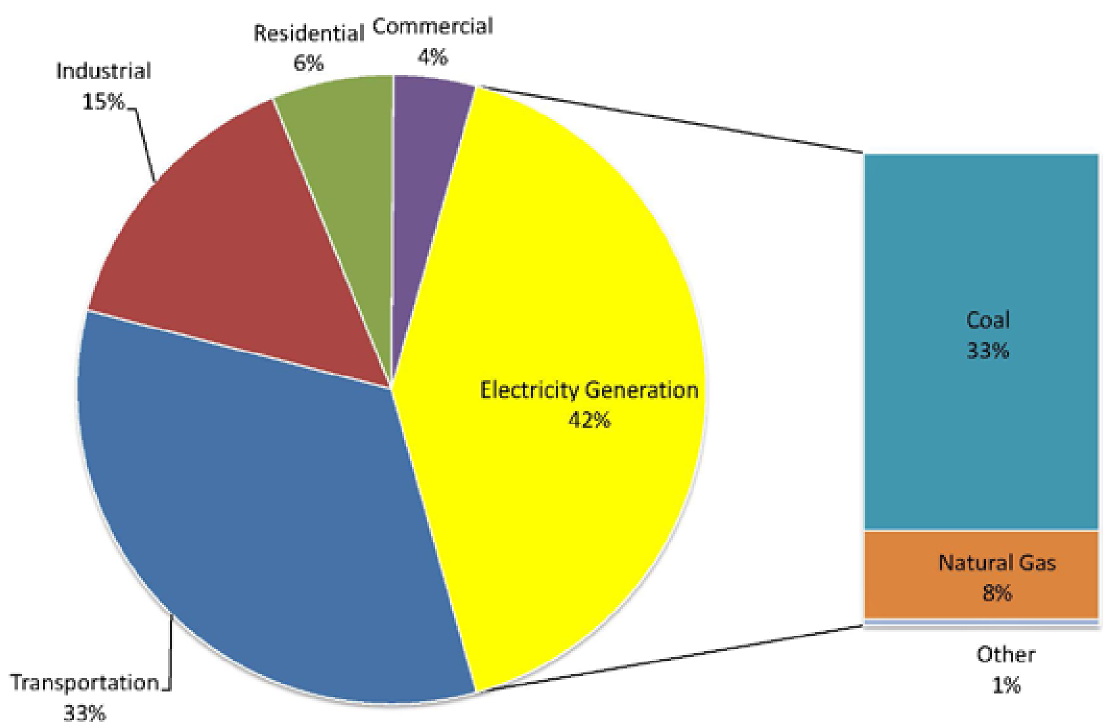
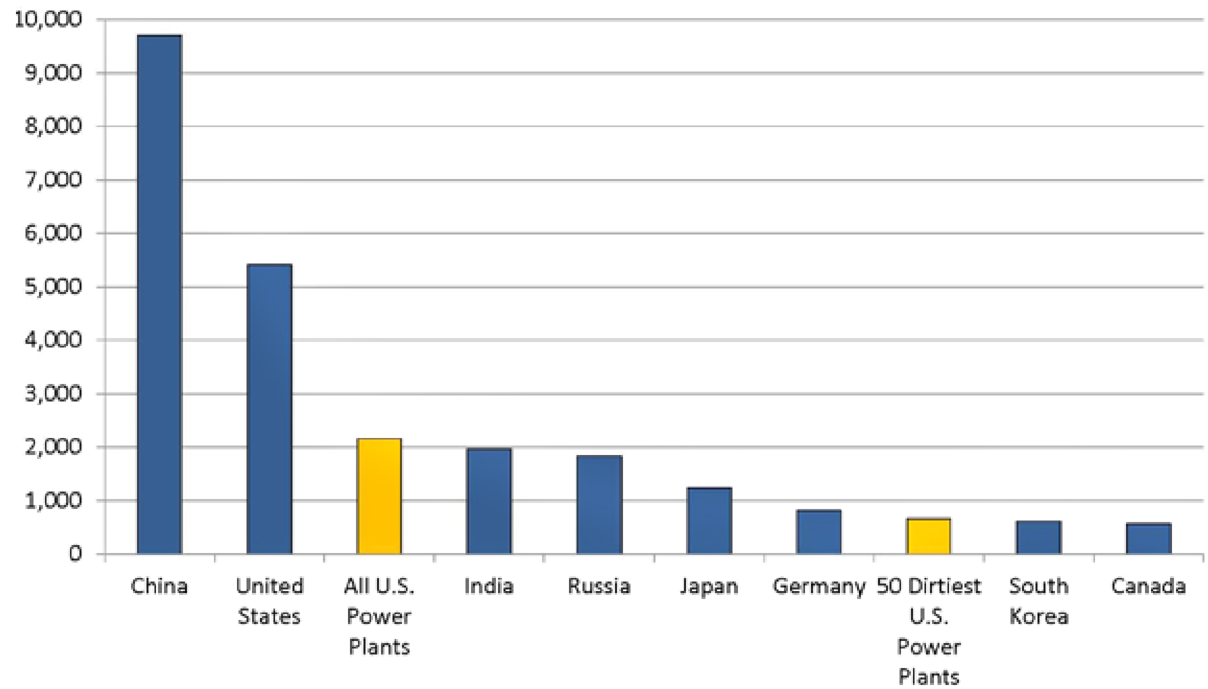


Figure 4. 50 Dirtiest U.S. Power Plants Compared to Total Emissions from Other Countries (MMT CO_2)[15]



America's power plants are also among the most significant sources of carbon dioxide pollution in the world. For example, if the U.S. power sector were an independent nation, it would be the third-largest emitter of carbon dioxide pollution in the world, behind China and the United States as a whole.[14] A large share of those emissions come from just a small number of old, dirty coal-fired power plants. The carbon dioxide pollution coming from America's 50 dirtiest power plants, for example, is greater than the amount of pollution produced annually by the entire economies of South Korea or Canada. (See Figure 4.)

The United States is already feeling the impacts of global warming. In the last 50 years the U.S. average annual temperature has risen 2° F, and experts project that it will continue rising.[16] Depending on the scale of continued greenhouse gas emissions, global average annual surface temperatures are likely to increase by 0.5°F to 8.6 °F by 2100, according to the most recent assessment by the Intergovernmental Panel on Climate Change (IPCC).[17]

Warmer average annual temperatures are connected to increases in extreme precipitation and more intense heat waves.[18] In the United States, extreme downpours now happen 30 percent more often nationwide than in 1948, and the largest annual storms now produce 10 percent more precipitation on average.[19] Meanwhile, the number of heat waves in the United States has increased since 1960 while the projected time between prolonged dry spells has become shorter.[20] The U.S. has also experienced an increase in the frequency and severity of other extreme weather events, including floods, more intense wildfires, and stronger tropical storms and hurricanes.[21]

Sea levels have risen eight inches along some parts of the U.S. coastline in the past 50 years. Rising seas erode shorelines—putting homes, businesses and infrastructure at risk—and can cause saltwater intrusion into coastal fresh water aquifers, leaving some unusable without desalination.[22] According to the IPCC, sea levels are likely to rise 10 to 32 inches by the late 21st century; in the worst case, sea levels could rise by as much as 38 inches.[23]

Science tells us that these and other impacts are expected to become more pronounced in the decades to come, unless we cut the dangerous carbon pollution that is fueling the problem. Increasing our production of wind power will help the United States make the emissions reductions necessary to forestall the worst impacts of global warming.

Power Plants Use Lots of Water

Fossil fuel power plants use vast amounts of water for cooling.

There are two ways to measure the use of water in power plants. *Withdrawals* represent the amount of water taken from waterways or groundwater for use in a power plant, regardless of whether that water is eventually returned to the river, lake or aquifer from which it came. More water is withdrawn from U.S. lakes, rivers, streams and aquifers to cool power plants than for any other purpose.[24] Water *consumption* reflects the amount of water that is lost to a given watershed as a result of its use in power plants, with losses primarily taking place through evaporation.

Almost all fossil fuel-fired power plants use water for cooling, but different power plant technologies have differing impacts on water supplies. Once-through cooling systems withdraw vast amounts of water for cooling and return it—usually at a higher temperature—to the waterways from which it came. Recirculating systems use the same water for cooling multiple times, reducing withdrawals, but plants with recirculating systems typically *consume* more water than once-through systems due to higher losses from evaporation.[25]

Regardless of the type of cooling system used, water use in power plants can create big problems for the environment. Large-scale water withdrawals for power plants can deplete groundwater supplies and affect the ecosystems of the waterways on which they depend. Fish and other aquatic life can be sucked into power plant intakes, while the discharge of heated water can also harm wildlife. Water discharged from a power plant can be 17 degrees hotter than it was when it was withdrawn for cooling.[26] This hotter water can affect the health and viability of the plants and animals living in the receiving waterway by subjecting organisms to water temperatures higher than they are able to tolerate and by depriving the waterway of dissolved oxygen. A 2013 study estimated that half of all power plant cooling systems discharge water at temperatures that can harm aquatic life.[27]

Recirculating cooling systems withdraw less water from waterways and aquifers, but lose more of that water to evaporation, potentially exacerbating local water supply problems. Many regions of the United States currently struggle to balance demands for water from industry, agriculture, and residential and commercial users while maintaining sufficient water levels in rivers and streams to preserve healthy ecosystems. Water consumption in power plants adds to those demands. In arid regions, power plants contribute to the long-term drawdown of critical groundwater supplies. In the Southwest and California, approximately one-third to two-thirds of the water consumed by power plants comes from groundwater.[28]

Power Plants Create Harmful Air Pollution

Coal- and natural gas-fired power plants also produce pollution that contributes to ozone smog, particulate matter and acid rain. This pollution hurts public health and ecosystems.

Each year, power plants are responsible for about 15 percent of the nation’s emissions of nitrogen oxides (NO_X) – a key ingredient in ozone smog.[29] When inhaled, ozone quickly reacts with airway tissues and produces inflammation similar to sunburn on the inside of the lungs. This inflammation makes lung tissues less elastic, more sensitive to allergens, and less able to ward off infections.[30] Minor exposure to ozone can cause coughing, wheezing and throat irritation. Constant exposure to ozone over time can permanently damage lung tissues, decrease the ability to breathe normally, and exacerbate or potentially even cause chronic diseases like asthma.[31] Children, adults who are active outdoors, and people with existing respiratory system ailments suffer most from ozone's effects.

Particulate matter pollution also contributes to a host of respiratory and cardiovascular ailments. Sulfur dioxide, too, is a respiratory irritant for sensitive populations.[32] It is also a major component of acid rain that has damaged forests across the eastern United States.[33] Power plants are responsible for nearly 60 percent of U.S. sulfur dioxide pollution annually.[34]

Finally, nearly two-thirds of all airborne mercury pollution in the United States in 2010 came from the smokestacks of coal-fired power plants.[35] Mercury is a potent neurotoxicant, and exposure to mercury during critical periods of brain development can contribute to irreversible deficits in verbal skills, damage to attention and motor control and reduced IQ.[36]

Wind Energy Reduces Pollution and Saves Water

In 2012, the United States generated 140,000 gigawatt-hours (GWh) of electricity from wind power—or as much as electricity as was used in the state of Georgia in 2011.[37] (See Appendix A for a breakdown of wind power generation and its benefits by state.)

Assuming that wind energy displaced generation from natural gas and coal-fired power plants, the environmental benefits of wind power in 2012 included:

- Avoided emissions of 84.7 million metric tons of carbon dioxide, the leading global warming pollutant—as much as would have been emitted by 17.6 million passenger vehicles in a year (see Appendix B).[38] That's more than all the energy-related carbon dioxide emissions in Massachusetts, Maryland, South Carolina or Washington state in 2011.[39]
- Water savings of nearly 38 billion gallons, more than enough to meet the annual domestic water needs of more than a million people (see Appendix C).[40]
- Reductions in air pollution, including reductions of 79,600 tons of nitrogen oxide emissions and 98,400 tons of sulfur dioxide emissions (see Appendix D).[41]

Texas reaps greater savings from wind energy than any other state, avoiding 19.3 million metric tons of carbon dioxide emissions annually, or about 8 percent of 2011 emissions from the state's electric sector.[42] (See Figure 5 and Table 1, next page.) In addition, as the state recovers from the extreme drought in 2011 that caused major rivers run dry, wind power is averting the consumption of at least 8.6 billion gallons of water per year, enough to supply the domestic water needs of more than 172,000 people.

Figure 5. Top 10 States for Carbon Dioxide Emission Reductions from Wind Power in 2012

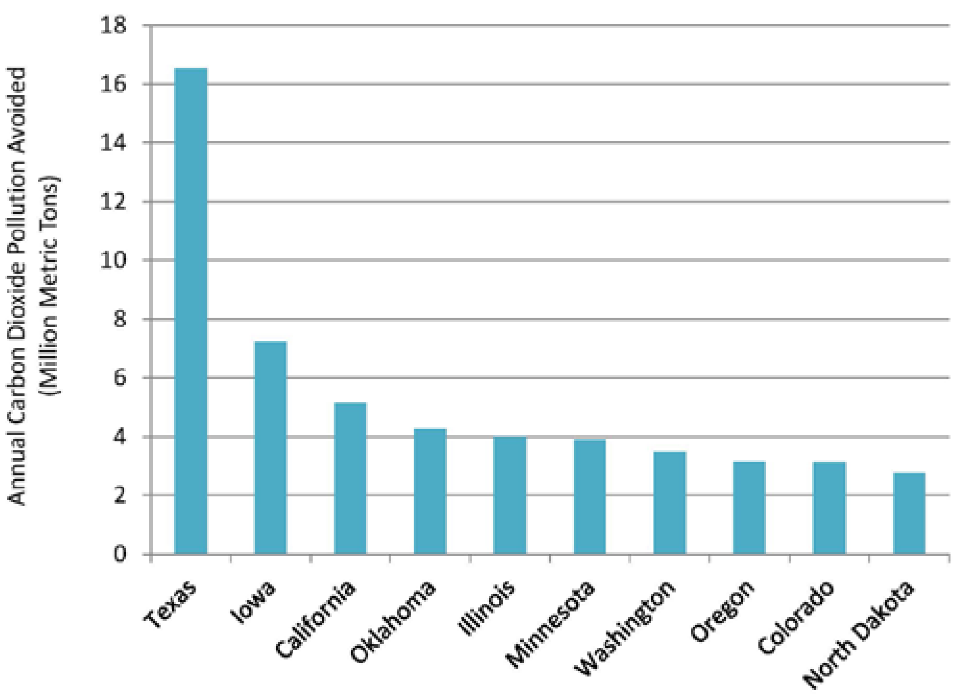


Table 1. Benefits of Wind Energy in Top 10 States, 2012

State	Wind Power Generation (GWh)	Avoided Carbon Dioxide Emissions (million metric tons)	Water Saved (million gallons)
Texas	31,860,000	19.3	8,610
Iowa	13,945,000	8.4	3,769
California	9,937,000	6.0	2,685
Oklahoma	8,234,000	5.0	2,225
Illinois	7,708,000	4.7	2,083
Minnesota	7,529,000	4.6	2,035
Washington	6,688,000	4.0	1,807
Oregon	6,066,000	3.7	1,639
Colorado	6,045,000	3.7	1,634
North Dakota	5,316,000	3.2	1,437

Seven of the top ten wind power-producing states are also on the list of states that suffered from areas of extreme or exceptional drought in 2012.[43] Collectively, wind power helped these seven states avoid consumption of 27.9 billion gallons of water at power plants, enough to serve the annual domestic water needs of 773,000 people—or nearly all the residents of Fort Worth.[44]

America Stands to Benefit Further if We Continue to Expand Wind Power

From the wide plains of the Midwest to the river valleys of the Pacific Northwest to the shores of the Atlantic Ocean, the United States has only scratched the surface of its vast wind energy potential. Tapping just a fraction of this potential by maintaining and expanding America's commitment to wind energy will produce even greater benefits.

Wind turbines can be placed virtually anywhere the wind blows. A 2012 report by the National Renewable Energy Laboratory estimates that as a whole, the United States has the technical potential to install nearly 11,000 GW of onshore wind capacity, and another 4,200 GW of offshore wind capacity.[45] (See Figures 6 and 7.) That amount of wind capacity could produce nearly 49.8 million GWh of electricity annually—12 times the amount of electricity generated in the United States in 2012.[46]

If the United States were to install wind energy between now and 2018 at the same pace that it did from 2007 to 2012, in five years, wind energy would help the United States:

- Avoid 157 million metric tons of carbon dioxide pollution annually—or as much as that emitted by 32 million of today's passenger vehicles in a year.[49] That's also more than all the energy-related emissions of Georgia, Michigan or New York in 2011.[50]
- Save enough water to supply the annual domestic water needs of 2.1 million people—roughly as many people as live in the city of Houston and more than live in Philadelphia, Phoenix or San Diego.
- Averting more than 121,000 tons of smog-forming nitrogen oxide pollution and 194,000 tons of sulfur dioxide pollution each year.

Figure 6: Onshore Wind Energy Technical Potential by State, 2012[47]

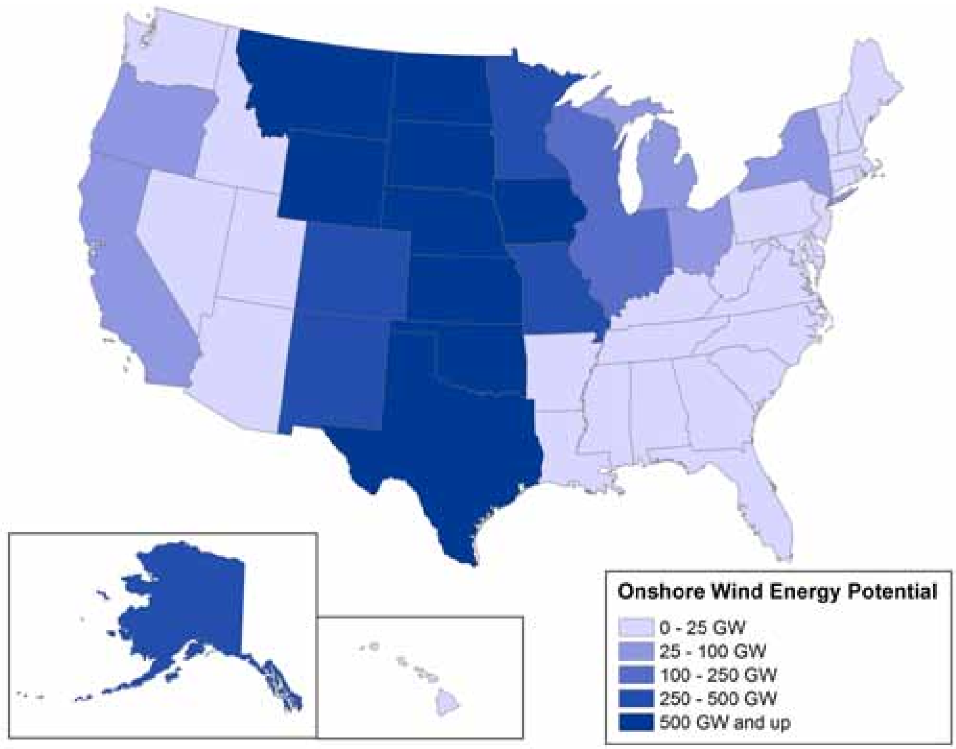
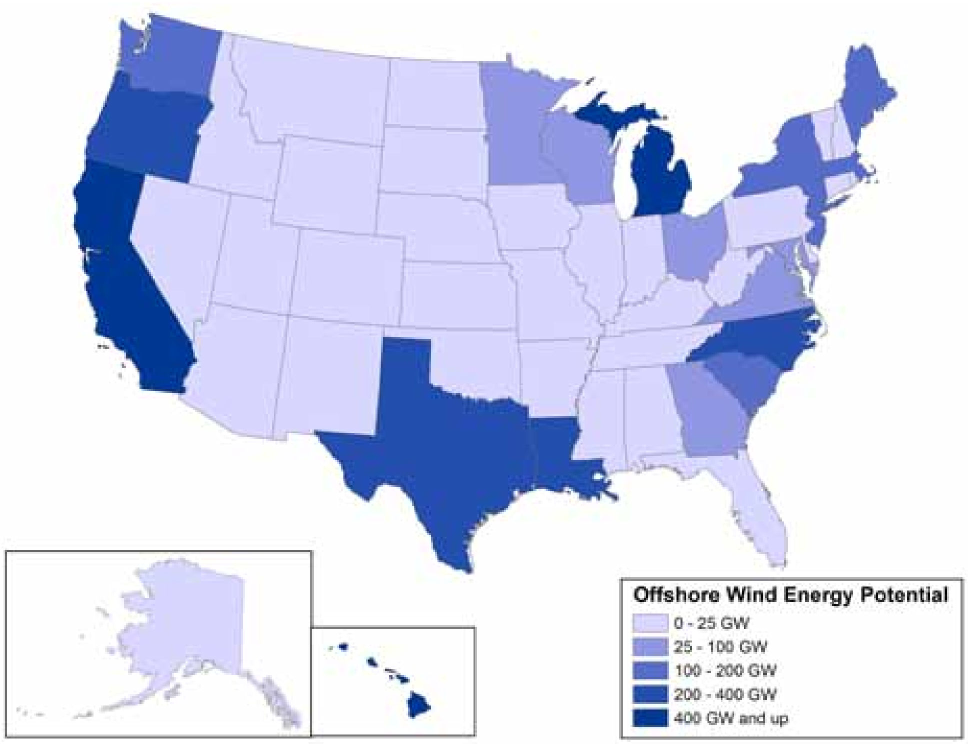


Figure 7: Offshore Wind Energy Technical Potential by State, 2012[48]



America Should Continue to Invest in Wind Energy

America's clean energy boom is no accident. It is the direct result of strong, forward-thinking policies adopted over the last decade at both the state and federal levels, policies that have unleashed the energy of innovative companies and American workers to fuel dramatic growth in renewable energy. As wind energy and other forms of clean, renewable energy take root in the United States—delivering ample benefits for our environment and economy—now is not the time to turn our back on further progress. To further reduce global warming pollution, curb smog and soot, move away from fossil fuels, save water, and grow our economy, the United States should make a long-term commitment to renewable energy with policies to support growth of the wind industry.

Federal Tax Incentives

Two of the most important tools that have helped grow the wind industry in the United States are the federal renewable electricity production tax credit (PTC) and the investment tax credit (ITC).

Policies such as the PTC and ITC recognize that renewable energy is a key component of an electricity grid that is not only cleaner but that also delivers stable, reasonable prices for consumers. Renewable energy sources such as wind are not subject to the fuel price volatility of coal and natural gas, and can deliver reliable, affordable electricity for decades, making them a smart long-term investment in the nation's energy future. However, renewable energy projects are often capital intensive. Unlike fossil fuel power plants, for which fuel costs represent a significant share of the overall cost of producing power, the vast majority of the costs of building a wind turbine or installing a solar panel are incurred before the first kilowatt-hour of electricity is produced. Public policies that defray some of those initial capital costs, or that help assure a reliable rate of return over the long term, can reduce the risk for investors—opening the floodgates for investment and the rapid expansion of renewable energy.

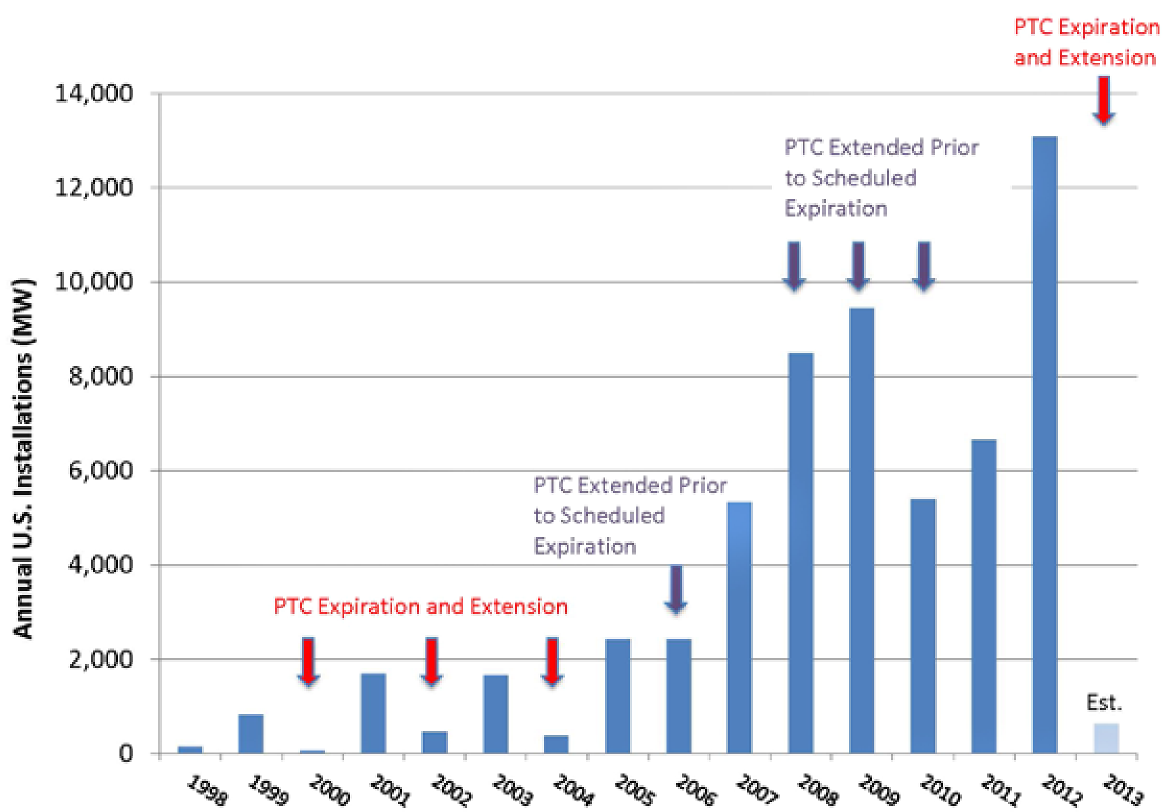
The PTC provides an income tax credit of 2.3 cents per kilowatt-hour (kWh) for utility-scale wind energy producers.[51] It is available for electricity generated during the first 10 years of the wind farm's operation. After expiring at the end of 2012, the PTC was renewed in January 2013 and will be available for all projects that begin construction on or before December 31, 2013.

The investment tax credit (ITC) covers up to 30 percent of the capital cost of new renewable energy investments, with the credit becoming available the moment the wind energy system is placed into service. The ITC also expires on December 31, 2013.[52]

Wind energy developers and other builders of renewable energy systems may choose to take advantage of either the PTC or the ITC, but not both. Different types of renewable energy projects stand to reap greater benefits from one or the other program, depending in part on the capital intensity of the project and the amount of power it produces over time.[53] Federal renewable energy tax credits have been a key contributor to the growth of wind energy over the last decade, but their effectiveness has been hamstrung by their "here today, gone tomorrow" inconsistency. Over the past 13 years, the renewable energy PTC has been available only sporadically. When the PTC has been renewed by Congress for only for one or two years at a time or even allowed to expire, the ensuing uncertainty has discouraged wind developers from building new capacity, stunting industry growth. For instance, in 2000, 2002 and 2004—years when the PTC was allowed to expire temporarily—new wind installations dropped by 93 percent, 73 percent and 77 percent, respectively, from the previous year when the PTC had been in force.[54] (See Figure 8.)

The economic uncertainty created by the sporadic availability of incentives discourages businesses that manufacture turbines, gear boxes, blades, bearings and towers from entering the market or expanding, restricting the supply chain and increasing costs. On the other hand, long-term consistency in renewable energy policy can encourage new businesses to enter the field and expand operations, bringing new jobs and investment to the United States. For example, between 2005-2006 and 2012—a period of relative stability in clean energy incentives—the amount of domestically produced content in U.S. wind power projects increased from 25 percent to 72 percent, creating new jobs and economic opportunity in the United States.[55]

Figure 8. The Impact of the Sporadic Expiration and Renewal of the PTC on the Wind Industry[56]



Establish Strong Renewable Electricity Standards

A renewable electricity standard (RES) helps support wind energy development by requiring utilities to obtain a percentage of the electricity they provide to consumers from renewable sources. These standards help ensure that wind energy producers have a market for the electricity they generate, as electricity suppliers seek to reach their required threshold for renewable electricity. This certainty makes it easier for wind developers to finance and build new wind power installations. Today, 29 states have renewable electricity standards.[57] From 1999 through 2012, 69 percent of all new wind capacity was built in states with renewable electricity standards.[58] In 2012, the proportion rose to 83 percent.[59] Some of the states with the strongest standards, such as Colorado, have seen the greatest growth in wind power generation.[60]

Renewable electricity standards have not only proven to be effective at spurring wind energy development, but they have also had little effect on ratepayers, with most policies resulting in either a small net benefit or a small cost to ratepayers on the order of $5 per year.[61] This does not include the economic value of the environmental and public health benefits of renewable energy, nor does it reflect the economic benefits of wind energy-driven job creation, leading to the conclusion that renewable electricity standards are a winner for both the environment and the economy.

In order for RES policies to continue to drive wind energy growth, however, states without RESs will need to adopt them, those with policies will need to strengthen them, and the federal government will need to adopt a national policy of its own. According to the U.S. Department of Energy, existing state RESs will drive the addition of only 3 to 5 GW of renewable energy per year between now and the end of the decade, which is lower than the amount of wind energy added in recent years.[62] Strengthening the nation's renewable energy goals will help keep the United States on pace to tap an increasing share of its wind energy potential.

Facilitate Development of Offshore Wind Resources

Some of the best wind energy resources are offshore. To capture that potential, policymakers need to set a bold goal for offshore wind development in the Atlantic. A goal will help articulate the important role of offshore wind in America's energy future. The Department of the Interior and the Bureau of Ocean Energy Management will need sufficient staff and resources to manage multiple renewable energy leases along the coast and to promote an efficient leasing process. A coordinated effort by federal, state and regional economic development, energy and commerce agencies is needed to develop commitments to purchase offshore wind power. Finally, offshore wind projects must be sited, constructed and operated responsibly in order to avoid and mitigate conflict with local marine life and other uses.

Methodology

Estimates of the benefits of wind energy were obtained by applying national assumptions regarding the amount of pollution or water consumption avoided per megawatt-hour (MWh) of wind energy to estimated wind energy production in 2012 and the amount of wind energy assumed to be produced in 2018 if the United States continues to add wind energy at a pace consistent with recent experience.

Data on annual wind generation (in MWh) for 2012 were obtained from Energy Information Administration, *Electric Power Monthly*, February 2013.

To estimate output from wind facilities in 2018, we assumed the installation of a modest 640 MW of new wind energy capacity in 2013, based on the assumption that approximately half of the 1,280 MW of new wind capacity under construction as of the end of the second quarter of 2013 would be completed by the end of the year.[63] We then assumed that the United States would add onshore wind capacity at a pace equivalent to the average annual addition of wind power capacity from 2007 to 2012, or 8,620 MW—a level of wind energy development well within the historical experience of the United States.

In addition to onshore wind energy, the United States has ample potential to develop wind energy resources in ocean waters and the Great Lakes. To date, the United States does not have any operational offshore wind energy facilities, but several such facilities are in development. Our analysis assumes that the United States will add 3.4 GW of wind energy capacity between 2013 and 2018, based on data from Navigant Consulting, *Offshore Wind Market and Economic Analysis: Annual Market Assessment*, prepared for the U.S. Department of Energy, 22 February 2013.

Table 2. Actual and Assumed Growth in Cumulative U.S. Wind Installations, 1999-2018[64]

Year	Wind Energy Capacity (MW)
1999	2,472
2000	2,539
2001	4,232
2002	4,687
2003	6,350
2004	6,723
2005	9,147
2006	11,575
2007	16,907
2008	25,410
2009	34,863
2010	40,267
2011	46,916
2012	60,007
Estimated onshore additions in 2013	640
Assumed onshore additions, 2014-18	43,100
Assumed offshore additions, 2013-18	3,380
Installed wind capacity at end of 2018	**107,127**

We apportioned new onshore wind energy capacity among the states according to their share of the nation's existing wind power capacity.[65] New offshore wind capacity was apportioned among the states based on the locations of the projects identified in the Navigant Consulting study.

To estimate electricity generation from these capacity additions in each state, we used regional capacity factors based on historical performance data for existing U.S. wind turbines, per Ryan Wiser and Mark Bolinger, *2011 Wind Technologies Market Report*, U.S. Department of Energy, August 2012. Because the state-level data did not include Alaska or Hawaii, we assumed wind projects in those states achieved the national average capacity factor of 33 percent. We assumed that the southeastern states have the same capacity factor as the East. The capacity factor for offshore wind projects is assumed to be 39 percent, based on U.S. Department of Energy, National Energy Technology Laboratory, *Role of Alternative Energy Sources: Wind Technology Assessment*, 30 August 2012.

Technological improvements could lead to significantly increased capacity factors for onshore and offshore wind installations in the near future. To the extent that those improvements develop and are implemented in U.S. wind energy projects, the environmental benefits presented here can be considered conservative estimates.

Estimating Carbon Dioxide Emission Reductions

When a wind turbine generates electricity, it displaces some other source of electricity on the grid. The type of electricity production that is offset by wind depends on several factors: regional variations in the electricity resource mix, the degree to which wind energy offsets new versus existing generation capacity, the relative price of competing forms of electricity generation (including marginal prices), and the way in which wind energy is integrated into the grid, among others.

In this report, we assume that 75 percent of the generation offset by wind energy is in the form of natural gas generation and 25 percent in the form of coal-fired generation. This simple assumption reflects the frequent status of natural gas as a marginal source of generation in much of the country, as well as the recent dominance of natural gas in proposals for new fossil fuel-fired generation capacity. For wind turbines installed through the end of 2012, we assume that the natural gas generation avoided shares the emission characteristics of existing natural gas power plants; for plants installed in 2013 and later years, we assume that wind offsets new natural gas combined cycle power plants.

The use of simplified national assumptions blurs regional variations in the emission reduction benefits of wind energy generation. In its 2012 market report, the American Wind Energy Association estimated that a megawatt-hour of electricity produced from a newly installed wind turbine will offset 1,300 pounds of carbon dioxide pollution on average nationally, but that the reductions would vary by region from as much as 1,630 pounds/MWh to as little as 970 pounds/MWh.[67] Readers should be aware of these potential regional variations in the emission benefits of wind energy and understand that the emission reductions estimated here may vary by as much as +/- 25 percent.

Table 3. Average Capacity Factor, Based on Projects Built from 2004-2010[66]

Region	Average Capacity Factor
East	25%
New England	28%
California	30%
Great Lakes	31%
Northwest	32%
Texas	34%
Mountain	36%
Heartland	37%
Offshore	39%

We calculated a national average carbon dioxide emissions rate for coal and natural gas plants for 2011 based on emissions figures for the electric power industry from U.S. Department of Energy, Energy Information Administration, *State Historical Tables for 2011*, February 2013, and net generation of electricity from U.S. Department of Energy, Energy Information Administration, *Electricity Data Browser*, accessed at www.eia.gov/electricity/data.cfm, 21 October 2013. For new natural gas-fired power plants, we used the emission rate given for a new natural gas combined cycle power plant without carbon capture and storage in U.S. Department of Energy, National Energy Technology Laboratory, *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant*, 30 September 2010.[68]

To put carbon dioxide emission reductions in perspective, we calculated how many passenger vehicles would have to be removed from the road in order to produce comparable savings. Data on vehicle emissions rates is from Environmental Protection Agency, *Clean Energy: Calculations and References*, updated 19 September 2013 and accessed at www.epa.gov/cleanenergy/energy-resources/refs.html.

It is important to note that U.S. power grids cross state lines, such that electricity generated in one state may be consumed in a neighboring state. The emission reductions attributed to each state in this report reflect the emissions impact of wind power produced within each state.

Estimating Avoided Water Consumption

We estimated water savings using freshwater consumption rates in coal and natural gas combined cycle power plants from U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply*, July 2008. We used the same assumption as for carbon dioxide savings that 75 percent of displaced generation is from natural gas power plants and 25 percent is from coal plants, with water consumption for combined cycle plants used to calculate savings for both existing and future wind power capacity. The U.S. DOE study used national estimates of water consumption due to the lack of regional variation in water consumption patterns among specific technologies, and used the same figures for current and future generation technologies.

In this report, we present data on water *consumption* by power plants, which is the amount of water lost to a watershed (usually through evaporation) as a result of power plant operation. We do not present data on water *withdrawals* for power plant operations. Withdrawals are also a critical measure of power plants' environmental impact as high levels of water withdrawals can have significant impacts on the environment and wildlife. By reducing the need for fossil fuel-fired power plants, wind energy can also reduce the amount of water withdrawn for power plant cooling.

We calculated the number of individuals whose domestic water needs could be met with this amount of saved water. We obtained state-level per capita domestic water use from Joan Kenny et al., *Estimated Use of Water in the United States in 2005*, U.S. Geological Survey, 2009.

As with estimates of the carbon dioxide emission benefits of wind power, estimates of water savings based on national averages may overstate or understate water savings experienced in a particular state, depending on the specific mix of electricity generation that is avoided through the use of wind energy.

Estimating Avoided Emissions of Nitrogen Oxides and Sulfur Dioxide

We also estimated avoided emissions of nitrogen oxides (NO_X) and sulfur dioxide (SO_2) by multiplying electricity generation from wind power by an annual emissions rate for each pollutant. We created an average annual emission rate for each pollutant assuming that 25 percent of the electricity displaced by existing wind generation would be from existing coal plants, and 75 percent from natural gas power plants. As with our estimates of carbon dioxide emission reductions, we assumed that wind turbines built through the end of 2012 offset emissions from natural gas-fired power plants at a rate characteristic of the existing generation fleet, while new wind turbines offset emissions at a rate characteristic of new natural gas combined cycle power plants.

We calculated a national average emissions rate for coal and natural gas plants for 2011 based on emissions figures for the electric power industry from U.S. Department of Energy, Energy Information Administration, *State Historical Tables for 2011*, February 2013, and net generation of electricity from U.S. Department of Energy, Energy Information Administration, *Electricity Data Browser*, accessed at www.eia.gov/electricity/data.cfm, 21 October 2013. For new natural gas-fired power plants, we used the emission rate given for a new natural gas combined cycle power plant without carbon capture and storage in U.S. Department of Energy, National Energy Technology Laboratory, *Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant*, 30 September 2010.[69]

As with the other estimates of environmental impacts in this report, reductions in nitrogen oxide and sulfur dioxide may vary by region depending on the specific characteristics of the electric grid in those areas, as well as regulatory limits on pollution from power plant smokestacks.

Can Wind Turbines Make You Sick?

By Kelsey Tsipis on Wed, 27 Jun 2018

The amount of wind power generated in America has nearly doubled in recent years. Today, the United States ranks first in the world for electricity generated from wind, according to the Department of Energy. But for some, the shifting winds of the renewable energy revolution isn't a pleasant one.

In places like Massachusetts, New York, and Vermont where industrial wind turbine projects have recently been introduced, residents have reported symptoms such as nausea, sleep disorders, fatigue, and increased stress that they account to a low-frequency hum—a combination of audible bass sounds and inaudible vibrations—generated by the turbines. In one instance, an air traffic controller attributed a near-fatal mistake on the insomnia and stress he experienced after a wind turbine was installed near his home in Falmouth, Massachusetts.

Twenty-five peer-reviewed studies have found that living near wind turbines does not pose a risk on human health.

As public support for renewable energy technologies like wind gains traction, some local communities are putting their foot down, arguing that these efforts shouldn't come at the expense of their health. But whether the sound, audible or inaudible, actually impacts human health remains a deeply contested issue.

Scientific consensus suggests it does not. Twenty-five peer-reviewed studies have found that living near wind turbines does not pose a risk on human health. The studies looked at a range of health effects from hearing loss, nausea, and sleep disorders to dizziness, blood pressure, tinnitus, and more. Recently, a new study using retrospective data reported that stress, as measured by hair cortisol levels, was not associated with proximity to wind turbines.

The study, published in the June issue of *The Journal of the Acoustical Society of America*, found no direct link between residents' distance from wind turbines in Ontario and Prince Edward Island and sleep disturbances, blood pressure, or stress. The stress levels were both self-reported and measured via hair cortisol levels, a hormone secreted under stress that prepares the body for its fight-or-flight response.

"It's not that we don't believe that people aren't feeling well or aren't sleeping well," said Sandra Sulsky, one of the study's co-authors and an epidemiologist at Ramboll, an international engineering consultancy company. "What we don't know is how that is related to presence or absence of a wind turbine."

The study used publically available data from a 2013 public health survey commissioned by the Canadian government, called the Community Noise and Health Survey, which is the only large-scale study on both subjective (self-reported symptoms) and objective (cortisol levels, blood pressure, heart rate, sleep monitoring) health outcomes in relation to living near wind turbines. Both the original 2013 study and new retrospective analysis found that wind turbine noise and proximity, respectively, were not associated with any adverse outcomes except for annoyance.

However, the results of the two studies deviated in one interesting way. The recent analysis found that the closer the respondents lived to wind turbines the lower they ranked the quality of life of their environment. The original study found no link between sound levels and these quality of life ratings. Though because there is no baseline data for the sample, Sulsky said, it's difficult to distinguish whether respondents were dissatisfied before the wind turbines were installed.

"But it does suggest that there's something other than sound itself that influences those perceptions," Sulsky said.

With no proven biological basis for the reported symptoms, some have pointed to the "nocebo effect" as the cause of the complaints. The nocebo effect is akin to the placebo effect, where an individual's positive perception towards a drug or treatment produces positive results, except in the nocebo effect, it's negative attitudes and negative results.

The idea that a nocebo effect may be driving people's reported problems is backed up by a 2014 study that pointed out that health complaints are more common in areas with the most negative publicity about the alleged harmful effects of turbines. A large-scale population survey in the Netherlands found that reports of stress and sleep disturbance were more common in areas where the turbines were visible.

For those living in the shadows of the wind turbines, there is little debate that the turbines have damaged their previously bucolic way of life. Annette Smith, the head of the group Vermonters for a Clean Environment and a long-time critic of industrial wind projects, said the projects have "destroyed the community."

"If you just talk to people who live around these things, there's no question that people are getting sick," Smith said.

Through the grassroots organization she heads, Smith has helped organize public hearings for residents who report serious illnesses as well as lost hobbies such as gardening due to infrasound vibrations. In one case, a resident named Luann Therrien, who lives less than a mile from a 400-foot turbine, said she initially supported the wind projects.

"We were not against the turbines before they went in [but after] we were dizzy, had vertigo like you wouldn't believe," she said at one hearing.

One theory from residents as to why these effects don't show up in the studies is that the Vermont mountains funnel the sound in a way that the flatlands of the Midwest do not. Others say some people may just be more susceptible than others to the inaudible noise, like sea sickness.

In response to these lobbying efforts, Smith said the utility companies have shown no willingness to talk about tangible solutions, such as real-time monitoring of noise, like what happens at airports. “They just deny it happens,” she said.

Apart from noise, Smith has what she calls “a menu” of other issues with industrial wind projects in residential areas. She cites the environmental effects of building roads and blasting ridge lines, changes to the topography of the land, and changes in wildlife populations. Smith, who lives “off the grid” with solar panels and the occasional diesel generator supplying her electricity, questions whether a commitment to this carbon-free source of electricity comes at too large of an expense to the rural communities that house them.

“We’re all expected to solve the energy issues of the world if we don’t want wind,” Smith said. “And I think that there are many other ways of developing and getting energy that people aren’t sacrificed or getting sick or leaving their homes… or being ridiculed.”

As to whether complaints from nearby residents will put a halt to wind power’s expanse in the U.S., recent data suggest they will not. From 2011 to 2016 electricity generated from wind turbines rose from 120 million to 226 million megawatt hours in the United States—a rise that also has not produced an increase in evidence of adverse health outcomes.

“It’s natural to look for causes, and something that seems to be new in the environment is a natural conclusion to draw,” Sulsky said. “But so far the evidence doesn’t support a causal association.”

Summary of main conclusions reached in 25 reviews of the research literature on wind farms and health.

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Reviews of the evidence - extracted highlights

Direct health effects from noise and WTS

- "There is no consistent evidence that noise from wind turbines—whether estimated in models or using distance as a proxy—is associated with self-reported human health effects. Isolated associations may be due to confounding, bias or chance." NHMRC (2014) full report

- "There are no direct pathological effects from wind farms and that any potential impact on humans can be minimised by following existing planning guidelines." *Source: NHMRC 2010*
http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "There is no evidence that the audible or sub-audible sounds emitted by wind turbines have any direct adverse physiological effects." *Source: Colby 2009 review*
http://199.88.77.35/EFiles/docs/CD/PlanCom/10_0426_IT_100416160206.pdf

- "... surveys of peer-reviewed scientific literature have consistently found no evidence linking wind turbines to human health concerns." *Source: CanWEA*
http://www.canwea.ca/pdf/CanWEA%20-%20Addressing%20concerns%20with%20wind%20turbines%20and%20human%20health.pdf

- "There is insufficient evidence that the noise from wind turbines is directly... causing health problems or disease." *Source: Massachusetts review*
http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

- “There is no reason to believe, based on the levels and frequencies of the sounds and... sound exposures in occupational settings, that the sounds from wind turbines could plausibly have direct adverse health consequences.” *Source: Colby 2009 review* http://199.88.77.35/EFiles/docs/CD/PlanCom/10_0426_IT_100416160206.pdf

- “... while some people living near wind turbines report symptoms such as dizziness, headaches, and sleep disturbance, the scientific evidence available to date does not demonstrate a direct causal link between wind turbine noise and adverse health effects. The sound level from wind turbines at common residential setbacks is not sufficient to cause hearing impairment or other direct health effects...” *Source: Ontario CMOH Report* http://www.health.gov.on.ca/en/public/publications/ministry_reports/wind_turbine/wind_turbine.pdf

- “... the audible noise created by a wind turbine, constructed at the approved setback distance does not pose a health impact concern.”*Source: Chatham-Kent Public Health Unit* http://www.harvestingwindsupport.com/blog/wp-content/uploads/2011/03/Chatham-KentHealth-and-Wind-.pdf

- There is no evidence for a set of health effects, from exposure to wind turbines that could be characterized as a "Wind Turbine Syndrome." *Source: Massachusetts review* http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

- “... there is not an association between noise from wind turbines and measures of psychological distress or mental health problems.” *Source: Massachusetts review* http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

- “Evidence that environmental noise damages mental health is… inconclusive.” *Source: Ad Hoc Expert Group on Noise and Health* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- “…no association was found between road traffic noise and overall psychological distress…”*Source: Ad Hoc Expert Group on Noise and Health* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- “To date, no peer reviewed scientific journal articles demonstrate a causal link between people living in proximity to modern wind turbines, the noise (audible, low frequency noise, or infrasound) they emit and resulting physiological health effects.” *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf
  “... there is no scientific evidence that noise at levels created by wind turbines could cause health problems other than annoyance...” *Source: Eja Pedersen 2003 Review* http://www.naturvardsverket.se/Documents/publikationer/620-5308-6.pdf

  “None of the... evidence reviewed suggests an association between noise from wind turbines and pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headache/migraine." *Source: Massachusetts review* http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

"...there are no evidences that noise from wind turbines could cause cardiovascular and psycho-physiological effects." *Source: Eja Pedersen 2003 Review* http://www.naturvardsverket.se/Documents/publikationer/620-5308-6.pdf

"…there was no evidence that environmental noise was related to raised blood pressure…"*Source: Ad Hoc Expert Group on Noise and Health* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- "The health impact of the noise created by wind turbines has been studied and debated for decades with no definitive evidence supporting harm to the human ear." *Source: Chatham-Kent Public Health Unit* http://www.harvestingwindsupport.com/blog/wp-content/uploads/2011/03/Chatham-KentHealth-and-Wind-.pdf

- "The electromagnetic fields produced by the generation and export of electricity from a wind farm do not pose a threat to public health..."*Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "... no consistent associations were found between wind turbine noise exposure and symptom reporting, e.g. chronic disease, headaches, tinnitus and undue tiredness." *Source: Bolin et al 2011 Review* http://iopscience.iop.org/1748-9326/6/3/035103/pdf/1748-9326_6_3_035103.pdf

- "... low level frequency noise or infrasound emitted by wind turbines is minimal and of no consequence... Further, numerous reports have concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "... renewable energy generation is associated with few adverse health effects compared with the well documented health burdens of polluting forms of electricity generation..." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "Although opposition to wind farms on aesthetic grounds is a legitimate point of view, opposition to wind farms on the basis of potential adverse health consequences is not justified by the evidence." *Source: Chatham-Kent Public Health Unit* http://www.harvestingwindsupport.com/blog/wp-content/uploads/2011/03/Chatham-KentHealth-and-Wind-.pdf

- "What is apparent is that numerous websites have been constructed by individuals or groups to support or oppose the development of wind turbine projects, or media sites reporting on the debate. Often these websites state the perceived impacts on, or benefits to, human health to support the position of the individual or group hosting the website. The majority of information posted on these websites cannot be traced back to a scientific, peer-reviewed source and is typically anecdotal in nature. In some cases, the information contained on and propagated by internet websites and the media is not supported, or is even refuted, by scientific research. This serves to spread misconceptions about the potential impacts of wind energy on human health..." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- Afsset was mandated by the Ministries responsible for health and the environment to conduct a critical analysis of a report issued by the *Académie nationale de medicine* that advocated the use of a minimum 1,500 metre setback distance for 2.5 MW wind turbines or more. The Affset report concluded that "It appears that the noise emitted by wind turbines is not sufficient to result in direct health consequences as far as auditory effects are concerned. [...] A review of the data on noise measured in proximity to wind turbines, sound propagation simulations and field surveys demonstrates that a permanent definition of a minimum 1,500 m setback distance from homes, even when limited to windmills of more than 2.5 MW, does not reflect the reality of exposure to noise and does not seem relevant."

Annoyance

- "... wind turbine noise is comparatively lower than road traffic, trains, construction activities, and industrial noise."*Source: Chatham-Kent Public Health Unit* http://www.harvestingwindsupport.com/blog/wp-content/uploads/2011/03/Chatham-KentHealth-and-Wind-.pdf

- "There is consistent evidence that noise from wind turbines—whether estimated in models or using distance as a proxy—is associated with annoyance, and reasonable consistency that it is associated with sleep disturbance and poorer sleep quality and quality of life. However, it is unclear whether the observed associations are due to wind turbine noise or plausible confounders" NHMRC (2014) full report

- "The perception of noise depends in part on the individual - on a person's hearing acuity and upon his or her subjective tolerance for or dislike of a particular type of noise. For example, a persistent "whoosh" might be a soothing sound to some people even as it annoys others."*Source: NRC 2007* http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

- "... some people might find [wind turbine noise annoying. It has been suggested that annoyance may be a reaction to the characteristic "swishing" or fluctuating nature of wind turbine sound rather than to the intensity of sound." *Source: Ontario CMOH Report* http://www.health.gov.on.ca/en/public/publications/ministry_reports/wind_turbine/wind_turbine.pdf

- "… being annoyed can lead to increasing feelings of powerlessness and frustration, which is widely believed to be at least potentially associated with adverse health effects over the longer term."*Source: Ad Hoc Expert Group on Noise and Health* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- "Wind turbine annoyance has been statistically associated with wind turbine noise, but found to be more strongly related to visual impact, attitude to wind turbines and sensitivity to noise." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- "... self reported health effects like feeling tense, stressed, and irritable, were associated with noise annoyance and not to noise itself..." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- "... many of the self reported health effects are associated with numerous issues, many of which can be attributed to anxiety and annoyance." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- "To date, no peer reviewed articles demonstrate a direct causal link between people living in proximity to modern wind turbines, the noise they emit and resulting physiological health effects. If anything, reported health effects are likely attributed to a number of environmental stressors that result in an annoyed/stressed state in a segment of the population." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- "… some community studies are biased towards over-reporting of symptoms because of an explicit link between…noise and symptoms in the questions inviting people to remember and report more symptoms because of concern about noise." *Source: Ad Hoc Expert Group on Noise and Health* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- "... it is probable that some persons will inevitably exhibit negative responses to turbine noise wherever and whenever it is audible, no matter what the noise level." *Source: Fiumicelli review abstract*

- "The major source of uncertainty in our assessment is related to the subjective nature of response to sound, and variability in how people perceive, respond to, and cope with sound." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "... sleep difficulties, as well as feelings of uneasiness, associated with noise annoyance could be an effect of the exposure to noise, although it could just as well be that respondents with sleeping difficulties more easily appraised the noise as annoying." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "Even noise that falls within known safety limits is subjective to the recipient and will be received and subsequently perceived positively or negatively."*Source: Chatham-Kent Public Health Unit* http://www.harvestingwindsupport.com/blog/wp-content/uploads/2011/03/Chatham-KentHealth-and-Wind-.pdf

- "... annoyance was strongly correlated with a negative attitude toward the visual impact of wind turbines on the landscape..." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "Respondents tended to report more annoyance when they also noted a negative effect on landscape, and ability to see the turbines was strongly related to the probability of annoyance."*Source: Minnesota Health Dept 2009* http://www.health.state.mn.us/divs/eh/hazardous/topics/windturbines.pdf

- "[It is proposed that annoyance is not a direct health effect but an indication that a person's capacity to cope is under threat. The person has to resolve the threat or their coping capacity is undermined, leading to stress related health effects... Some people are very annoyed at quite low levels of noise, whilst other are not annoyed by high levels." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "Further, sounds, such as repetitive but low intensity noise, can evoke different responses from individuals… Some people can dismiss and ignore the signal, while for others, the signal will grow and become more apparent and unpleasant over time… These reactions may have little relationship to will or intent, and more to do with previous exposure history and personality." *Source: Minnesota Health Dept 2009* http://www.health.state.mn.us/divs/eh/hazardous/topics/windturbines.pdf

- "Stress and annoyance from noise often do not correlate with loudness. This may suggest [that other factors impact an individual's reaction to noise… individuals with an interest in a project and individuals who have some control over an environmental noise are less likely to find a noise annoying or stressful." *Source: Minnesota Health Dept 2009* http://www.health.state.mn.us/divs/eh/hazardous/topics/windturbines.pdf

- "There is a possibility of learned aversion to low frequency noise, leading to annoyance and stress..." *Source: Leventhall 2005 review* http://www.noiseandhealth.org/article.asp?issn=1463-1741;year=2004;volume=6;issue=23;spage=59;epage=72;aulast=Leventhall

- “Noise produced by wind turbines generally is not a major concern for humans beyond a half mile or so because various measures to reduce noise have been implemented in the design of modern turbines.”*Source: NRC 2007*
  http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

- “Noise… levels from an onshore wind project are typically in the 35-45 dB(A) range at a distance of about 300 meters... These are relatively low noise or sound-pressure levels compared with other common sources such as a busy office (~60 dB(A)), and with nighttime ambient noise levels in the countryside (~20-40 dB(A)).” *Source: NRC 2007*
  http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

- “Complaints about low frequency noise come from a small number of people but the degree of distress can be quite high. There is no firm evidence that exposure to this type of sound causes damage to health, in the physical sense, but some people are certainly very sensitive to it.” *Source: Ad Hoc Expert Group on Noise and Health*
  http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

- “… there is the theoretical possibility that annoyance may lead to stress responses and then to illness. If there is no annoyance then there can be no mechanism for any increase in stress hormones by this pathway… if stress-related adverse health effects are mediated solely through annoyance then any mitigation plan which reduces annoyance would be equally effective in reducing any consequent adverse health effects. It would make no difference whether annoyance reduction was achieved through actual reductions in sound levels, or by changes in attitude brought about by some other means.” *Source: Ad Hoc Expert Group on Noise and Health*
  http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1279888026747

Infrasound

- “Infrasound is audible when the sound levels are high enough. The hearing threshold for infrasound is much higher than other frequencies. Infrasound from wind farms is at levels well below the hearing threshold and is therefore inaudible to neighbouring residents. There is no evidence that sound which is at inaudible levels can have a physiological effect on the human body . This is the case for sound at any frequency, including infrasound.”
  http://docs.health.vic.gov.au/docs/doc/5593AE74A5B486F2CA257B5E0014E33C/$FILE/Wind%20farms,%20sound%20and%20%20health%20-%20Technical%20information%20WEB.pdf

- "Claims that infrasound from wind turbines directly impacts the vestibular system have not been demonstrated scientifically... evidence shows that the infrasound levels near wind turbines cannot impact the vestibular system."
  http://www.mass.gov/dep/public/press/0112wind.htm
- “There is no evidence that infrasound ... [from wind turbines ... contributes to perceived annoyance or other health effects.” *Source: Bolin et al 2011 Review*
  http://iopscience.iop.org/1748-9326/6/3/035103/pdf/1748-9326_6_3_035103.pdf

- "There is no consistent evidence of any physiological or behavioural effect of acute exposure to infrasound in humans." *Source: UK HPA Report* http://www.hpa.org.uk/webc/HPAwebFile/HPAweb_C/1265028759369

- "... self reported health effects of people living near wind turbines are more likely attributed to physical manifestation from an annoyed state than from infrasound." *Source: Knopper&Ollson review* http://www.ehjournal.net/content/pdf/1476-069X-10-78.pdf

- "... infrasound from current generation upwind model turbines [is well below the pressure sound levels at which known health effects occur. Further, there is no scientific evidence to date that vibration from low frequency wind turbine noise causes adverse health effects." *Source: Ontario CMOH Report* http://www.health.gov.on.ca/en/public/publications/ministry_reports/wind_turbine/wind_turbine.pdf

- "It would appear... that infrasound alone is hardly responsible for the complaints... from people living up to two km from the large downwind turbines." *Source: Jakobsen 2005 review* http://multi-science.metapress.com/content/w6r4226247q6p416/

- "From a critical survey of all known published measurement results of infrasoundfrom wind turbines it is found that wind turbines of contemporary design with therotor placed upwind produce very low levels of infrasound. Even quite close to theseturbines the infrasound level is far below relevant assessment criteria, including thelimit of perception."*Source: Jakobsen 2005 review* http://multi-science.metapress.com/content/w6r4226247q6p416/

- "With older downwind turbines, some infrasound also is emitted each time a rotor blade interacts with the disturbed wind behind the tower, but it is believed that the energy at these low frequencies is insufficient to pose a health hazard." *Source: NRC 2007* http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

Shadow flicker

- "Scientific evidence suggests that shadow flicker [from the rotating blades of wind turbines does not pose a risk for eliciting seizures as a result of photic stimulation." *Source: Massachusetts review* http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

- Shadow flicker from wind turbines… is unlikely to cause adverse health impacts in the general population. The low flicker rate from wind turbines is unlikely to trigger seizures in people with photosensitive epilepsy. Further, the available scientific evidence suggests that very few individuals will be annoyed by the low flicker frequencies expected from most modern wind turbines." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpa ctAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "Flicker frequency due to a turbine is on the order of the rotor frequency (i.e., 0.6-1.0 Hz), which is harmless to humans. According to the Epilepsy Foundation, only frequencies above 10 Hz are likely to cause epileptic seizures." *Source: NRC 2007* http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

Community & social response to wind turbines

- The perception of sound as noise is a subjective response that is influenced by factors related to the sound, the person, and the social/environmental setting. These factors result in considerable variability in how people perceive and respond to sound... Factors that are consistently associated with negative community response are fear of a noise source... [and noise sensitivity..." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "Wind energy developments could indirectly result in positive health impacts... if they increase local employment, personal income, and community-wide income and revenue. However, these positive effects may be diminished if there are real or perceived increases in income inequality within a community." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "Effective public participation in and direct benefits from wind energy projects (such as receiving electricity from the neighboring wind turbines) have been shown to result in less annoyance in general and better public acceptance overall." *Source: Massachusetts review* http://www.mass.gov/dep/energy/wind/turbine_impact_study.pdf

- "... people who benefit economically from wind turbines [are less likely to report noise annoyance, despite exposure to similar sound levels as those people who [are not economically benefiting." *Source: NHMRC 2010* http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/new0048_evidence_review_wind_turbines_and_health.pdf

- "Landowners... may perceive and respond differently (potentially more favorably) to increased sound levels from a wind turbine facility, particularly if they benefit from the facility or have good relations with the developer..." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "The level of annoyance or disturbance experienced by those hearing wind turbine sound is influenced by individuals' perceptions of other aspects of wind energy facilities, such as turbine visibility, visual impacts, trust, fairness and equity, and the level of community engagement during the planning process." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "Wind energy facilities... can indirectly result in positive health impacts by reducing emissions of [green house gases and harmful air pollutants, and... Communities near fossil-fuel based power plants that are displaced by wind energy could experience reduced risks for respiratory illness, cardiovascular diseases, cancer, and premature death." *Source: Oregon review* http://public.health.oregon.gov/HealthyEnvironments/TrackingAssessment/HealthImpactAssessment/Documents/Oregon%20Wind%20Energy%20HIA%20Public%20comment.pdf

- "The environmental and human-health risk reduction benefits of wind-powered electricity generation accrue through its displacement of electricity generation using other energy sources (e.g., fossil fuels), thus displacing the adverse effects of those other generators." *Source: NRC 2007* http://www.vawind.org/assets/nrc/nrc_wind_report_050307.pdf

- "Community engagement at the outset of planning for wind turbines is important and may alleviate health concerns about wind farms. Concerns about fairness and equity may also influence attitudes towards wind farms and allegationsabout effects on health. These factors deserve greater attention in future developments." *Source: Ontario CMOH Report* http://www.health.gov.on.ca/en/public/publications/ministry_reports/wind_turbine/wind_turbine.pdf

Summary of 2013 VTA Finnish report

VTT Technical Research Centre of Finland has published a new study with a conclusion that wind turbines do not cause any adverse health effects. The study consisted of a review of nearly 50 scientific research articles conducted in Europe, USA, Australia and New Zealand over the past 10 years.

Due to the increased number of wind power projects in Finland, a growing concern has arisen among the public regarding the possible negative impacts wind energy production may have on human health. VTT Technical Research Centre of Finland conducted a comprehensive literature review covering nearly 50 scientific research articles. The review concluded that in the light of current scientific research, there is no evidence to show that the infrasound produced by modern wind turbines is anything but harmless.

The sound of a nearby wind farm is does not possess such qualities or volume that it would cause physical symptoms to humans. The study also concluded that the infra sounds below the auditory threshold does not constitute a health hazard. Additionally, most of the infra sound caused by a wind farm is mixed with other infra sound from the environment and does therefore not cause any additional exposure. According to the research articles reviewed, the low frequency sound with potential hazardous health impacts would have to be of a higher volume than that caused by wind farms, in order to have an impact on our health. Also, concern that shadow flicker may cause epileptic seizures are overruled in the research material. Such seizures cannot be caused by the type of flicker the slow rotation speed of the wind turbine blades produce.

Commentary: Major problems with recent systematic review on wind farms and distress.

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At least 20 reviews of the evidence on whether wind turbines cause health problems including stress have been published since 2003 (1). Cureus recently published another (2) where the authors referenced none of these.

Highlights of the findings of these reviews may be found here (1). The most recent (2014) review by Australia's peak health and medical agency, The National Health and Medical Research Council (3) concluded:

"There is no consistent evidence that noise from wind turbines… is associated with self reported human health effects. Isolated associations may be due to confounding, bias or chance. There is consistent evidence that noise from wind turbines—whether estimated in models or using distance as a proxy—is associated with annoyance, and reasonable consistency that it is associated with sleep disturbance and poorer sleep quality and quality of life. However, it is unclear whether the observed associations are due to wind turbine noise or plausible confounders."

and

"The association between estimated noise level and annoyance was significantly affected by the visual attitude of the individual (i.e. whether they found wind farms beautiful, or ugly and unnatural) in the three studies that assessed this as a potential confounding factor. Residents in [one] study with a negative attitude to the visual impact of wind farms on the landscape had over 14 times the odds of being annoyed compared with those people without a negative visual attitude. …This means that factors other than the noise produced by wind turbines contribute to the annoyance experienced by survey respondents."

Against this background, I was curious to see what a new systematic review would conclude. According to the Cureus website, the new paper was peer reviewed. This is difficult to understand because of the sheer volume of major and minor problems it contains. Together, these make its contribution valueless to scholarly understanding of the phenomenon of noise and health complaints about wind farms. The paper shows many signs of poor understanding of the subject matter of their review, of critical appraisal methods, of some basic conventions in systematic reviewing, of structuring in scientific writing, and much more besides.

The problems commence in the first line of the abstract where the confusing statement is made that "the proximity of wind turbines to residential areas has been associated with a higher level of complaints compared to the general population." I assume here that they are trying to say that those living near turbines have a higher prevalence of health complaints like sleep disturbance and general "human distress" than in the wider population. The prevalence of sleeping problems in general populations is as high as 33% (4) and reference material exists that quantifies the prevalence of many health problems in general populations (5, 6). Instead, the authors support their statement with a reference to a small qualitative study of 15 people both affected and unaffected by turbines (7). No conclusions about the prevalence of health problems in communities near turbines or in matched comparison populations can be drawn from that paper. I know of no published evidence that would allow such a statement to be made.

The authors state that their search strategy located 18 eligible papers but that these were based on six original studies. They explain that the 12 non-original "studies" (several of which were reviews or commentaries) were then excluded. Yet in their "key results" they proceed to describe the characteristics of all 18 papers and thus act as if these were not excluded ("All 18 peer-reviewed studies captured in our review found an association…").

The authors do not appear to understand what an "outcome" is. The abstract lists "outcome" variables that are not outcomes at all (such as study quality and journal name). These are independent variables, not dependent ones.

Their eligibility criteria for study selection are perplexing. What for example, is the difference between "peer-reviewed studies" and "studies published in peer-reviewed journals"? So too, is their noting that they searched the Cochrane Library for relevant studies. The Cochrane Library is a repository of reviews of evidence for health interventions, not for data on the prevalence of health complaints.

The authors seem not to understand the difference between studies and trials. For obvious reasons, there have been no trials conducted in this area.

Their main conclusions are that:

An association exists between wind turbines and distress in humans.

The existence of a dose-response relationship (between distance from wind turbines and distress) and the consistency of the association across studies .. argues for the credibility of this association.

The first conclusion is very imprecise and sweeping and ripe for being megaphoned by anti-wind farm interest groups as if it actually meant something. One of the six original studies reviewed (Salt & Hullar) (8) should have never been included in this review – see below. The Nissenbaum et a study (9) is listed as of moderate quality with a low risk of bias. Yet all three authors and two out of three reviewers of that paper are members of Society for Wind Vigilance, an anti-wind organization. Nissenbaum has been raising health concerns in study areas for several years, potentially biasing collected data. Neither of these problems is mentioned in this review. Two critiques of this study were published in Noise and Health pointing out the very poor quality of the results, analysis and the overstatements of conclusions (10, 11).

The Shepherd et al study (12) which the authors rate as of “high” quality, failed to make any mention that the small wind farm community involved had for years been subjected to a local wind farm opposition group fomenting anxiety about health issues (13). Indeed, with one exception (14), the five studies referenced were performed in areas where complaints of annoyance were being raised. But such farms are unlikely to be representative of all wind farms. As our work shows, over nearly 65% of wind farms in Australia have never received a single complaint (15), and 73% of complainants in Australia are concentrated around just 6/51 farms. The failure of the authors to note this fundamental problem of study sample selection bias is another major problem.

Among the five “original” studies they considered satisfied their selection criteria was a paper by Salt & Hullar (8). This paper is not in any way a “study” of “the association between wind turbines and human distress.” It reports no original empirical data and is essentially a backgrounder on infrasound and the “possibility” that wind turbine might create auditory distress. It is unfathomable why this paper was included in the data set.

Table 2 purports to be a meaningful summary of the findings of these six studies on the association between turbine exposure and “distress”. I would defy anyone to make any sense of the Table, particularly the column headed “does [sic] response”.

By way of comparison to the lack of detail provided by the authors of this review, it is instructive to look at the results from the Dutch study which formed the basis of the

Pedersen 2009 paper(14) which were further analysed by Bakker et al (16) who noted that sleep disturbance was assessed by a question dealing with the frequency of sleep disturbance by environmental sound ("how often are you disturbed by sound?"). Two thirds of all respondents reported not being disturbed by any sound at all. Disturbance by traffic noise or other mechanical sound was reported by 15.2% of the respondents. Disturbance by the sound of people and of animals was reported by 13.4% of the respondents. Relevantly, disturbance by the sound of wind turbines was reported by only 4.7% of the respondents (6% in areas deemed to be quiet and 4% in areas deemed to be noisy). Bakker and colleagues (16) note that it was not clear from the study if there was a primary source causing sleep disturbance and how respondents attributed being awakened by different environmental sound sources. What was clear was that wind turbines were less frequently reported as a sleep disturbing sound source, than other environmental sounds irrespective of the area type (quiet versus noisy). Analysis showed that among respondents who could hear wind turbine sound, annoyance was the only factor that predicted sleep disturbance. The authors speculated that being annoyed might contribute to a person's sensitivity for any environmental sound, and the reaction might be caused by the combination of all sounds present. It might also be the case that people annoyed by wind turbine noise attribute their experience of sleep disturbance to wind turbine noise, even if that was not the source of their awakening.

Swathes of the paper are given over to descriptions of their efforts to rate the levels of evidence in the four reviewed studies. But they never ever describe their approach in any way that might permit replication of how they went about such rating. How was level of evidence actually determined? It should have been explicitly defined in the text. Their discussion of the risk of bias across studies is bizarre. "The quality of the study could be confounded by journal name and author". Surely the authors mean here that the evaluation of the quality of the study could be biased by this knowledge. The term "confounded" has another meaning.

Their "key results" consist of no more than five bullet points. These read like draft notes-to-self (eg: None of these studies captured in our review found any association (potential publication bias)".

The authors chose to use the term "distress" instead of "annoyance". The American Medical Dictionary defines distress as 1. Mental or physical suffering or anguish or 2. Severe strain resulting from exhaustion or trauma. Annoyance on the other hand is defined as 1. The act of annoying or the state of being annoyed or 2. A cause of irritation or vexation; a nuisance. (The American Heritage Dictionary of the English Language, Fourth Edition copyright 2000) and is generally identified as a highly subjective state in medical literature. It is clear that the authors chose a stronger term than was used by the majority of studies. Most literature refers to annoyance, while the referenced alternative of "Wind Turbine Syndrome" was coined in a vanity press published case study with extraordinary weaknesses of selection bias, methodology and analysis (17). Similarly, "extreme annoyance" is rarely used in the literature. Annoyance is by far the most commonly used term in the material referenced, so it is unclear why “distress” was chosen.

The paper is riddled with imprecise, mangled and contradictory language. For example: key finding 1: “All 18 peer-reviewed studies captured in our review found an association…” and key finding 2: “None of these studies captured in our review found any association (potential publication bias)”; infelicitous prose: “these complaints are coined in research”; “There might be a theoretical incline to give studies in high impact journals higher quality…”; basic grammatical errors: “the study’s principle outcome”; “there was no missing data.” It is unconventionally structured with extremely scant results and methods sections providing no adequate explanations of how key decisions on quality or bias were made.

The publication of this very poor paper is regrettable.

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Using residential proximity to wind turbines as an alternative exposure measure to investigate the association between wind turbines and human health

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Using residential proximity to wind turbines as an alternative exposure measure to investigate the association between wind turbines and human health

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This analysis uses data from the Community Noise and Health Study developed by Statistics Canada to investigate the association between residential proximity to wind turbines and health-related outcomes in a dataset that also provides objective measures of wind turbine noise. The findings indicate that residential proximity to wind turbines is correlated with annoyance and health-related quality of life measures. These associations differ in some respects from associations with noise measurements. Results can be used to support discussions between communities and wind-turbine developers regarding potential health effects of wind turbines. © *2018 Acoustical Society of America.*
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I. INTRODUCTION

Despite support for developing renewable energy sources, wind farm projects have been the subject of controversy. The human health concerns that have been raised have been attributed to exposures to audible sound, low-frequency sound pressures (i.e., sub-audible or "infra-sound"), vibrations and shadow flicker patterns from the rotation of the blades (Feder *et al.*, 2015; McCunney *et al.*, 2014; Michaud *et al.*, 2012). To date, the epidemiological literature has demonstrated an association between wind turbine noise and annoyance, between wind turbine noise and quality of life indicators, and between wind turbine noise and sleep disturbances (Michaud *et al.*, 2016; Onakpoya *et al.*, 2015).

Health Canada and Statistics Canada conducted a study of wind turbines and health, the Community Noise and Health Survey (CNHS), which included both objective and subjective measures of health and exposure (Feder *et al.*, 2015; Michaud *et al.*, 2012). Several rigorous analyses have been published that examine the relationship between objective measures of wind turbine noise (WTN) and self-reported sleep-related measures, quality of life indicators, stress-related responses, health effects, and annoyance.

The main exposure used in the Community Noise and Health Survey was modelled outdoor A-weighted wind turbine sound pressure levels using the ISO 9613-1 and the ISO 9613-2 (Feder *et al.*, 2015; Keith *et al.*, 2016). This measure is based on manufacturers' octave band sound power spectra at an assumed wind speed of 8 m/s. It assumes that the dwelling is located downwind of the sound source, that there is a stable atmosphere, and that there is a moderate ground based temperature inversion (Feder *et al.*, 2015; Keith *et al.*, 2016). The manufacturers' sound power levels were validated for 10 of the 399 wind turbines included in the study (Keith *et al.*, 2016). Published findings from the Community Noise and Health Survey suggest that wind turbine noise is not associated with any adverse outcomes except for annoyance (Michaud *et al.*, 2016).

A-weighted measures are a standard method of quantifying exposure to wind turbine noise, although there is some debate over which noise measurement approach is the most appropriate to relate to human response (Keith *et al.*, 2016). If the reported annoyance is not due to noise, then sound pressure levels may serve as a surrogate for factors that are more closely associated with annoyance. We aimed to evaluate whether some aspect of living in proximity to wind turbines, perhaps summarized as a subjective experience, may explain the health and annoyance effects of WTN that have been reported in the CNHS and other studies. The CNHS dataset allows for direct comparison between analyses that evaluate the association between the objective WTN measure (i.e., sound pressure levels), and analyses evaluating residential distance to wind turbines as a measure that might capture at least some of the subjective element of wind turbine (WT) exposure.

II. METHODS

A. Study sample

The study sample comprised people living in proximity to a wind turbine in Ontario or Prince Edward Island, who participated in the CNHS, a one-time survey conducted in 2012–2013. The sample size was 1238 people. Sampling methods are described in multiple previous papers by Michaud *et al.* (2012, 2015, 2016). To summarize, all homes within 600 m of wind turbine were selected, and homes up to 10 km from wind turbines were randomly selected. One participant from each residence who was between ages 18−79 yr was selected randomly to participate. No substitutions were permitted. The response rate was 78.9% (Michaud *et al.*, 2012).

B. Analysis

Distance to wind turbines in kilometres was used as the primary predictor to build each of the models. Distance was modelled as a continuous variable and log-transformed to

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normalize the distribution. The outcomes of interest included quality of life indicators in the environmental, physical, social, and psychological domains measured using the WHOQOL-BREF (WHOQOL Group, 1998). The environment domain included the following facets: financial resources, freedom, physical safety and security, social care, home environment, opportunities for new skills and information, recreation, and leisure activities. The physical health domain included the following facets: activities of daily living, energy and fatigue, mobility, dependence on medicinal substances, pain and discomfort, sleep and rest, and work capacity. The social relationships domain included: personal relationships, social support, and sexual activity. The psychological domain included: body image, negative and positive feelings, self-esteem, and spirituality, thinking, learning, memory and concentration. Other outcomes of interest included reported annoyance, sleep measures (rate of awakenings, sleep efficiency, sleep latency, awakenings after sleep onset, and total sleep time) measured with sleep actigraphs, sleep quality measured using the Pittsburgh Sleep Quality Index, blood pressure, hair cortisol levels, perceived stress measured using the perceived stress scale and heart rate.

Potential covariates were explored through multiple individual multivariable analyses where each potential covariate was modelled to predict the outcomes of interest. If the p-value for the relationship between the potential covariate and the outcome of interest was less than 0.20, the covariate was included in the final model (Jewell, 2003). Then, stepwise elimination was performed to exclude covariates with a p-value greater than 0.10. Potential for interaction terms and effect modification by province were examined. Generalized estimating equations (GEE) were used for repeated-measures data. For each outcome, province and reported personal benefit were forced in the final models; this is consistent with the methods described by Michaud *et al.* (Michaud, 2015; Michaud *et al.*, 2016). A second analysis was also completed where distance was substituted as the primary predictor in models previously developed by Michaud *et al.* and Feder *et al.* (Feder *et al.*, 2015; Michaud, 2015; Michaud *et al.*, 2016). This was a direct substitution, and the final models are identical, with the same covariates as those obtained using modelled WTN as the primary predictor of interest. Data management and analysis was completed using SAS version 9.4 (SAS Institute, 2013).

III. RESULTS

Results suggest that proximity to wind turbines is inversely associated with the environment domain quality of life score ($\beta = -1.23$, SE $= 0.145$, $p = 0.046$). This association suggests that every kilometre a person lives further away from a wind turbine is associated with a 1.23 point increase in score on the environmental health quality of life scale (Table I). A higher score is indicative of a higher environmental quality of life. The marginal means presented in this table show the group means for levels of each variable, controlling for all other covariates in the model. For example, people who report experiencing migraines have a lower mean environmental quality of life score (mean score = 15.18) compared to those that do not report having migraines (mean score = 15.55, $p < 0.001$), when accounting for all other covariates.

Distance to wind turbines was also found to be strongly associated with increased annoyance (OR = 0.19; 95% CI = 0.07, 0.53, $p = 0.001$). This suggests that the odds of reporting being annoyed by a turbine are reduced by about 20% for every kilometer a person lives further away from a wind turbine (Table II).

In models where proximity to wind turbines was directly substituted into the models developed using modelled wind turbine noise, the association between distance to wind turbines and annoyance was also statistically significant and demonstrated a decrease in the likelihood of annoyance with increasing residential distance from the turbine (OR = 0.31; 95% CI: 0.11, 0.84, $p = 0.022$). Michaud *et al.* also found a significant association between wind turbine noise and annoyance (OR = 2.38, 95% CI: 1.42, 3.99) (Michaud *et al.*, 2016). There was a positive association between distance to wind turbines and the scores for the physical health quality of life domain ($\beta = 1.26$, SE $= 0.20$, $p = 0.043$) where there was not a significant association between wind turbine noise and physical health [Least squared means (LSM) = 13.111 95% CI: 12.32, 13.90 for < 25 dB vs LSM = 13.45, 95% CI: 12.81, 14.10 for 40−46 dB, $p = 0.1689$] (Feder *et al.*, 2015). There were no statistically significant associations found between residential proximity to wind turbines and the other outcomes.

IV. DISCUSSION

These results show that living closer in proximity to wind turbines is negatively correlated with self-rated environmental quality of life and physical health quality of life. These findings suggest that the mechanism of effect may not be noise, or not noise alone, and may include visual sight, vibrations, shadow flicker, sub-audible low frequency sound, or mechanisms that include individual subjective experiences and attitudes towards wind turbines. These data are consistent with findings published by Shepherd *et al.* who reported that those living within 2 km of a wind turbine scored lower on both physical and environmental domains also measured using the WHOQOL-BREF, than those in a comparison group among people living in semirural New Zealand (Shepherd *et al.*, 2011). These findings are also consistent with the findings by Onakpoya *et al.* where a systematic review demonstrated an association between wind turbine noise and annoyance, and between wind turbine noise and quality of life measures (using varied instruments; Onakpoya *et al.*, 2015). The difference in findings for the different exposure measures (modeled noise vs residential distance) could also be due to characteristics of the measurements, however. Specifically, distance is measured on a continuous scale, whereas wind turbine noise was also measured on a continuous scale but then categorized, ignoring variation within each category. Also, modelled sound measures were based on multiple measures (including distance) and therefore possibly susceptible to greater measurement error.

The associations between residential distance to wind turbines and both environmental and physical quality of life scores could indicate visual disturbances due to the presence of

TABLE I. Environment domain modelled with distance as primary predictor and wind turbine noise as a primary predictor.

Variable	Groups in variable	Marginal means[a] (95% CI) ($R^2 = 0.24$, n = 985)	*p*-Value	Marginal means[b] (95% CI) ($R^2 = 0.24$, n = 985)	*p*-Value
Distance to wind turbine		1.23 (0.145)[a]	0.046		
WTN levels (dB)	<25	—		16.28 (15.58–16.98)	0.368
	25–<30	—		15.71 (14.99–16.44)	
	30–<35	—		15.75 (15.16–16.34)	
	35–<40	—		15.82 (15.28–16.36)	
	40–46	—		15.73 (15.17–16.28)	
Province	PEI	15.27 (14.69–15.85)	0.285	15.76 (15.15–16.36)	0.276
	ON	15.46 (15.00–15.94)		15.96 (15.45–16.47)	
Personal benefit from having wind turbine in the area	Yes	15.42 (14.80–16.04)	0.618	15.92 (15.26–16.57)	0.632
	No	15.31 (14.85–15.76)		15.80 (15.31–16.29)	
Age group	≤24	15.78 (15.03–16.53)	<0.001	16.34 (15.56–17.12)	<0.001
	25–44	14.95 (14.42–15.48)		15.45 (14.90–16.00)	
	44–64	14.93 (14.43–15.43)		15.42 (14.89–15.95)	
	65+	15.81 (15.25–16.37)		16.22 (15.63–16.82)	
Level of education	≤High school	—		15.60 (15.06–16.14)	0.023
	Trade/certificate/college	—		15.67 (15.13–16.21)	
	University	—		16.31 (15.63–16.99)	
Income	<60k	14.79 (14.29–15.30)	<0.001	15.33 (14.78–15.89)	<0.001
	60–100k	15.44 (14.90–15.98)		15.95 (15.37–16.52)	
	≥100k	15.86 (15.31–16.42)		16.29 (15.72–16.87)	
Property ownership	Own	15.54 (15.05–16.03)	0.091	16.05 (15.52–16.58)	0.059
	Rent	15.19 (14.62–15.77)		15.66 (15.06–16.27)	
Facade type	Fully bricked	15.60 (15.07–16.12)	0.046	16.09 (15.53–16.64)	0.079
	Partially bricked	15.26 (14.68–15.85)		15.74 (15.12–16.35)	
	No brick/other	15.24 (14.74–15.74)		15.75 (15.21–16.30)	
Number of years hearing wind turbines	Do not hear wind turbines	—		15.89 (15.38–16.39)	0.073
	Less than 1 year	—		16.10 (15.35–16.86)	
	1 year or more	—		15.59 (15.05–16.12)	
Wind turbine annoyance	Yes	15.64 (15.15–16.13)	<0.0001	—	0.001
	No	15.09 (14.45–15.73)		—	
Visual annoyance to turbines	High	15.18 (14.65–15.71)	0.005	15.58 (14.97–16.18)	
	Low	15.55 (15.03–16.07)		16.14 (15.60–16.68)	
Turbine shadow flicker annoyance	High	15.11 (14.59–15.62)	0.055	16.08 (15.43–16.73)	0.092
	Low	15.63 (15.01–16.23)		15.64 (15.11–16.16)	
Alcohol use	None	15.32 (14.78–15.86)	0.002	15.79 (15.22–16.37)	0.069
	≤3 Times per month	15.23 (14.73–15.75)		15.73 (15.19–16.28)	
	1–3 Times/week	15.65 (15.11–16.19)		16.14 (15.56–16.72)	
	≥4 Times/week	15.25 (14.66–15.85)		15.77 (15.15–16.39)	
Smoking status	Current	15.04 (14.50–15.58)	<0.0001	15.56 (14.98–16.13)	0.013
	Former	15.45 (14.92–15.98)		15.95 (15.39–16.51)	
	Never	15.61 (15.08–16.13)		16.07 (15.51–16.62)	
Migraines	Yes	15.18 (14.65–15.71)	<0.001	15.68 (15.12–16.24)	0.035
	No	15.55 (15.03-16.07)		16.04 (15.49–16.59)	
Dizziness	Yes	15.11 (14.58–15.64)	<0.001	15.58 (15.01–16.21)	0.001
	No	15.63 (15.11–16.14)		16.14 (15.59–16.69)	
Tinnitus	Yes	15.16 (14.63–15.68)	0.003	15.65 (15.09–16.21)	0.013
	No	15.58 (15.06–16.10)		16.06 (15.51–16.62)	
Chronic pain	Yes	15.10 (14.59–15.63)	<0.001	15.60 (15.04–16.16)	0.001
	No	15.62 (15.11–16.14)		16.12 (15.57–16.66)	
Asthma	Yes	15.11 (14.49–15.72)	0.030	15.61 (14.96–16.25)	0.037
	No	15.63 (15.15–16.10)		16.11 (15.60–16.622)	
High blood pressure	Yes	15.22 (14.68–15.77)	0.044	—	
	No	15.50 (15.01–16.00)		—	
Diagnosed sleep disorder	Yes	15.07 (14.48–15.66)	0.010	15.51 (14.89–16.14)	0.002
	No	15.66 (15.17–16.15)		16.20 (15.68–16.73)	

[a]Distance as primary predictor.
[b]Wind turbine noise as a primary predictor.

TABLE II. Multiple logistic regression model.

	Multiple logistic regression model[a] (n = 1086, R^2 = 0.62, H-L p = 0.428)		Multiple logistic regression model[b] (n = 934, R^2 = 0.58, H-L p = 0.702)	
Variable	OR (CI)	p-value	OR (CI)	p-value
Distance to wind turbine (per km)	0.19 (0.07–0.53)	0.001	—	—
Wind turbine noise (dB)	—	—	2.38 (1.42–3.99)	0.001
Province	12.13 (2.14–68.21)	0.005	4.98 (1.15–21.58)	0.032
Closure of bedroom window due to wind turbines	5.03 (1.80–14.05)	0.002	8.45 (3.67–19.46)	<0.001
Hear traffic noise	0.36 (0.15–0.85)	0.021	—	—
Annoyance with blinking lights	—	—	3.26 (1.40–7.56)	0.006
Annoyance with vibrations, rattles	3.79 (1.14–12.61)	0.030	3.99 (1.22–13.07)	0.023
Visual annoyance to wind turbine	6.89 (3.41–13.95)	<0.001	2.77 (1.22–6.29)	0.015
Closure of bedroom window due to road traffic	0.39 (0.16–0.95)	0.037	0.42 (0.17–1.05)	0.063
Sensitivity to noise	3.27 (1.56–4.86)	0.002	2.11 (0.97–4.59)	0.061
Concerned about physical safety	2.59 (1.13–5.93)	0.024	2.56 (1.08–6.07)	0.033
Complaint about wind turbine	3.45 (0.92–12.94)	0.067	3.22 (0.85–12.20)	0.085
Air conditioner in dwelling	0.40 (0.14–1.13)	0.083	—	—
Window type (ref = single pane)			—	—
Double pane	0.062 (0.10–3.99)	0.616	—	—
Triple pane	0.06 (001–0.84)	0.037	—	—
Tinnitus	2.43 (1.18–5.03)	0.016	—	—
Environmental quality of life domain	0.73 (0.60–0.88)	0.001	—	—
Psychological quality of life domain	1.15 (0.99–1.34)	0.063	—	—

[a]Annoyance outcome with distance to wind turbine.
[b]Annoyance outcome with wind turbine noise.

turbines, greater disturbances or stresses at a neighbourhood-wide level, or the effects of poor relations with the wind power companies. Alternatively, the wind turbines might have been situated in locations where quality of life and environmental factors were already compromised. The cross-sectional design of the survey will not distinguish between effects caused by and those simply correlated with distance to the turbines.

The association found between proximity to wind turbines and annoyance is consistent with the findings reported by Michaud *et al*. (2016) where modelled WTN was found to be associated with annoyance (OR = 2.38; 95% CI: 1.42, 3.99; Table II). Our findings strengthen the argument that wind turbines are associated with annoyance, as this association is now found with both modelled A-weighted sound pressure levels and with residential distance to wind turbines. Other research has found that individuals reporting annoyance due to environmental noise also report health conditions including ischemic heart disease, depression, and migraines (Babisch *et al*., 2003; Maschke and Niemann, 2007). A recent study conducted in China found that noise sensitivity, attitudes towards the visual impact of wind turbines on the surrounding landscape, general opinions on wind turbines and noise intensity moderates the relationship between WTN and annoyance (Song *et al*., 2016). Together, these data suggest that preventive measures, including positive engagement between the community and the wind power companies, could reduce annoyance among residents.

Our analysis has limitations. Raw sound data were not available to us with the Community Noise and Health dataset. Only background-level noises and the modelled wind turbine sound were. Therefore, it was not possible to model sound using alternative methods, such as using G-weighted modelled sound, which would better account for low frequency sound waves (Jakobsen, 2001). Additional limitations are that the CNHS was a cross-sectional study and causality cannot be inferred, and that it may be subject to volunteer bias, where those who have strong feelings about wind turbines—either negative or positive—may be more likely to participate in the survey. Additionally, "survivor bias" may be present as those most affected by WTN may be more likely to have moved away from the wind turbines. Our team did not have access to information about those who were not included in the final study sample, although Michaud *et al*. reported that response rates did not vary by province or by proximity to wind turbines (Michaud, 2015). Finally, we did not have access to environmental quality scores prior to the installation of the wind turbines. It is possible that neighbourhoods closer in proximity to wind turbines already had conditions that result in perceived lower environmental and physical health quality of life prior to the installation of the wind turbines.

Through using an alternative wind turbine exposure measurement, this analysis demonstrated that living in close proximity to wind turbines is associated with lower environmental and physical quality of life measures. It also strengthened the notion that wind turbines are associated with annoyance, by finding a significant association between closer residential proximity to wind turbines and increased annoyance. Future research could focus on alternative exposures related to wind turbines that may be related to human health besides noise. Studies that examine outcomes prior to and following wind turbine installations may be better positioned to examine the potential causal association between wind turbines and health, and should include both specific, objective exposure measures and validated measures of the subjective experience of living near a wind farm.

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