Regional variations in the health, environmental, and climate benefits of wind and solar generation

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When wind or solar energy displace conventional generation, the reduction in emissions varies dramatically across the United States. Although the Southwest has the greatest solar resource, a solar panel in New Jersey displaces significantly more sulfur dioxide, nitrogen oxides, and particulate matter than a panel in Arizona, resulting in 15 times more health and environmental benefits. A wind turbine in West Virginia displaces twice as much carbon dioxide as the same turbine in California. Depending on location, we estimate that the combined health, environmental, and climate benefits from wind or solar range from \$10/MWh to \$100/MWh, and the sites with the highest energy output do not yield the greatest social benefits in many cases. We estimate that the social benefits from existing wind farms are roughly 60% higher than the cost of the Production Tax Credit, an important federal subsidy for wind energy. However, that same investment could achieve greater health, environmental, and climate benefits if it were differentiated by region.

externalities | renewable electricity | renewable energy policy | air pollution

Wind and solar power provide health, environmental, and climate benefits by displacing conventional generators and therefore reducing emissions of carbon dioxide (CO_2) and criteria air pollutants, which include sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$). It is natural to think that the windiest or sunniest sites will yield the best performance. However, the reduction in emissions resulting from wind or solar depends not only on the energy produced but also on the conventional generators displaced, and that varies dramatically depending on location.

Previous research has explored the emissions implications of renewable energy (1–7). The US Department of Energy estimates that achieving 20% wind penetration in the United States would reduce CO_2 emissions by 825 million metric tons by 2030 (1). Valenteno et al. (2) estimate the avoided emissions resulting from wind energy in Illinois, with a focus on the effects of additional cycling of conventional power plants. The study finds that 10% wind penetration would result in a 12% reduction in CO_2 emissions, 13% reduction in NO_x, 8% reduction in SO_2, and an 11% reduction in PM. Lu et al. (3) estimate that the CO_2 reductions resulting from 30% wind penetration in Texas would cost approximately \$20 per ton avoided. Kaffine et al. (4) estimate the emissions savings from wind energy for three regions of the United States. The study concludes that "emissions reductions in the Upper Midwest roughly cover government subsidies for wind generation, [while] environmental benefits in Texas and California fall short."

These studies vary greatly in the methods and assumptions used, the regions and pollutants covered, and the metrics reported, all of which prevent meaningful comparisons among studies. This work provides a systematic assessment of wind and solar energy across the United States. We estimate the monetized social benefits resulting from emissions reductions, and we explicitly consider differences in energy production, climate benefits from displaced CO_2 emissions, and health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$. In addition, we compare the social benefits from existing wind farms with the cost of the Production Tax Credit, an important federal subsidy for wind energy.

Results

We evaluate a Vestas V90-3.0-MW wind turbine at more than 33,000 locations and a 1-kW photovoltaic (PV) solar panel at more than 900 locations across the United States. We assume that wind and solar displace the damages from marginal electricity production, which varies regionally and temporally. Damages from CO_2 emissions are monetized using a social cost of \$20 per ton of CO_2. Location-specific damages from SO_2, NO_x, and $PM_{2.5}$ emissions are adopted from the Air Pollution Emission Experiments and Policy (APEEP) analysis model, which values mortality from air pollution at \$6 million per life lost (often termed the value of a statistical life) (8). For more than 1,400 fossil-fueled power plants, dollar-per-ton damage values for each pollutant are combined with plant-level emissions data to estimate the health, environmental, and climate damages for each hour from 2009 through 2011. Finally, we use regressions of measured hourly emissions and generation data to estimate the reduction in damages that occurs when conventional generators are displaced by wind or solar. To account for regional differences, regressions are performed separately for the 22 subregions defined in the Emissions and Generation Resource Integrated Database (eGRID). eGRID subregions were created by the US Environmental Protection Agency (EPA) using Power Control Areas as a guide. Although not perfect, they provide an estimate for the group of plants serving loads within a region (9).

Results are presented in Fig. 1. For both wind (Fig. 1 *A–C*) and solar (Fig. 1 *D–F*), we consider three measures of performance: capacity factor, which is the ratio of the annual energy production to the maximum energy production at full-power operation (Fig. 1 *A* and *D*); annual avoided CO_2 emissions (Fig. 1 *B* and *E*); and annual health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$ emissions (Fig. 1 *C* and *F*). For consistency, we provide all results on a per-kilowatt-installed or per-megawatt-hour basis. All monetary values are in 2010 dollars.

Social Benefits of Wind Energy. From an energy standpoint, wind turbines perform best in the Great Plains south through west Texas, where capacity factors can exceed 40%. The wind resource is poor in much of the West and moderate in much of the East. It is also poor in the Southeast, which is excluded from our assessment owing to data limitations (Fig. S1).

We report two metrics for reductions in CO_2 emissions—kilograms of CO_2 avoided annually and the corresponding social benefits, assuming a social cost of \$20 per ton of CO_2. Wind turbines are most effective at displacing CO_2 emissions when located in the Midwest, where the wind resource is excellent and

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Data deposition: A spreadsheet of the full results reported in this paper for both wind and solar is available at http://cedmcenter.org/tools-for-cedm/marginal-emissions-factors-repository/.

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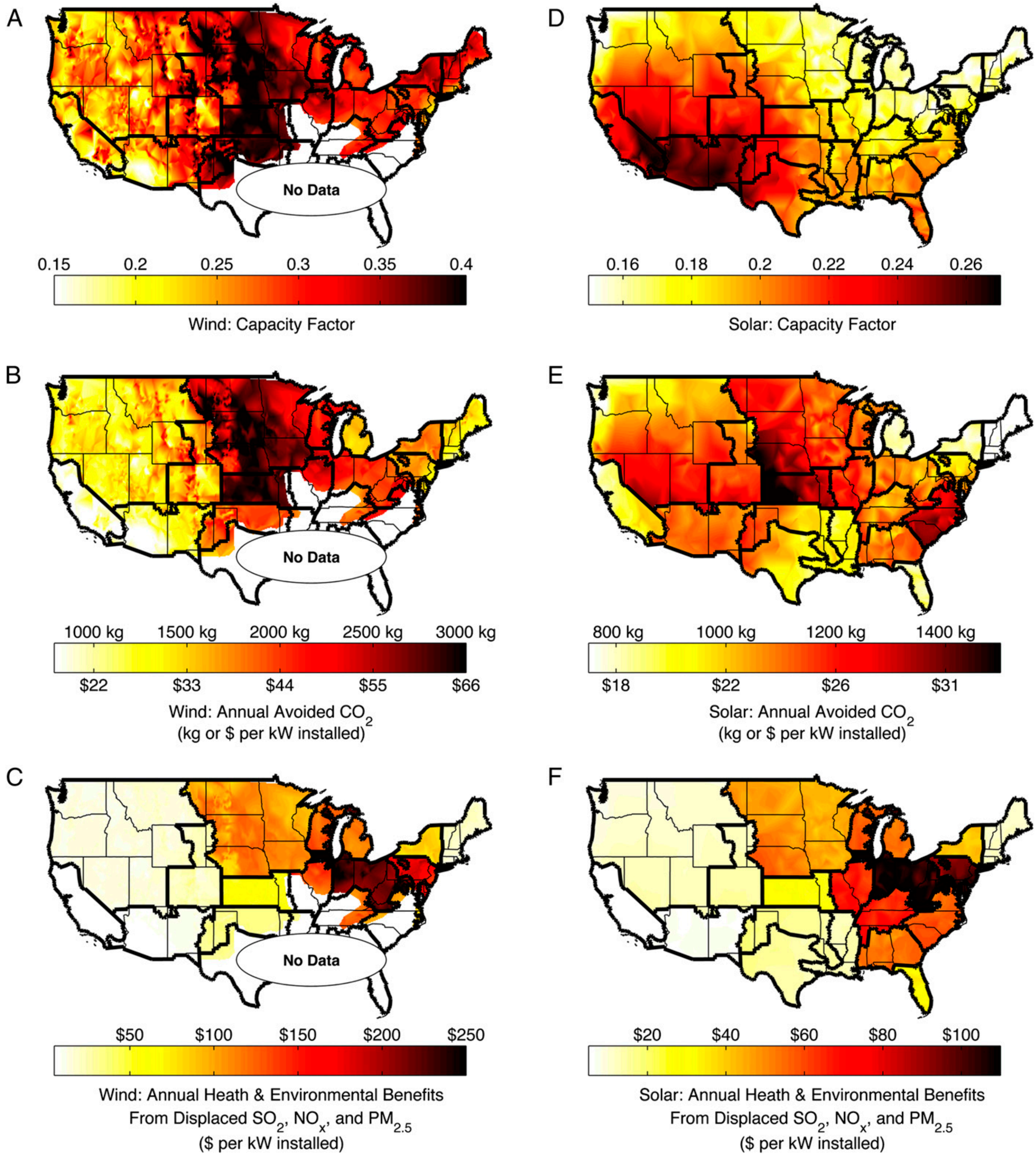

Fig. 1. Performance of wind turbines (*A–C*) and solar panels (*D–F*) relative to three objectives: capacity factor, a measure of energy output (*A* and *D*); annual avoided CO_2 emissions and the corresponding social benefits, assuming a social cost of \$20 per ton of CO_2 (*B* and *E*); and annual health and environmental benefits from displaced SO_2, NO_x and $PM_{2.5}$ emissions (*C* and *F*). Because of data limitations, the eastern part of Texas and the Southeast are excluded from our assessment of wind energy. Sharp boundaries are due to the assumption that wind and solar only affect generators within the same eGRID subregion (i.e., imports and exports of electricity between regions are ignored). Monetary values are in 2010 dollars.

wind energy primarily displaces coal-fired generators. Sites in Oklahoma, Texas, and California are less beneficial because gas-fired plants, with relatively low CO_2 rates, are predominantly displaced. Because of the relatively clean sources of electricity and the modest wind resource, wind turbines in California are among the least effective at displacing CO_2 emissions. A wind turbine at the best site in California displaces 20% less CO_2 compared with an average site in Ohio.

Per kilowatt of installed wind capacity, the annual value of displaced CO_2 emissions ranges from \$23 in Rhode Island to \$65 in Kansas, equivalent to \$11/MWh and \$18/MWh. Because results are linearly related to the social cost of CO_2, the benefits of displaced emissions double if we assume costs of \$40 rather than \$20 per ton.

Previous studies by Kaffine et al. (6) and Cullen (7) have estimated that wind energy in Texas displaces ∼470 and 650 kg of CO_2 per MWh, reasonably consistent with our estimate of 560 kg/MWh.

By displacing SO_2, NO_x, and $PM_{2.5}$ from conventional generators, a wind turbine in West Virginia avoids \$230 in health and environmental damages per kilowatt per year (\$81/MWh)—7 times more than a wind turbine in Oklahoma and 33 times more than a wind turbine in California. Damages from SO_2, NO_x, and $PM_{2.5}$ are dominated by human-health effects. Muller et al. (10) used the APEEP model to estimate the annual damages from criteria pollutants in the United States, finding that 71% of total damages are from premature mortality and 23% are from illnesses. The combined impacts from reduced visibility, agricultural and timber losses, and degradation of materials made up only 6% of total damages. Because we value all premature deaths at \$6 million, and Muller et al. used life-years lost, the results presented here place a higher value on human mortality. As a result, human-health effects will account for a greater share of total damages.

On average, wind turbines in California provide \$7/kW in annual health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$; the same turbine in Indiana provides \$245/kW in annual benefits (\$3/MWh and \$83/MWh). These regional variations are driven by differences in the generation mix. In much of the Midwest and mid-Atlantic, wind energy primarily displaced coal-fired generators. The National Research Council found that the monetized health and environmental damages from the median coal-fired plant are 20 times higher compared with the median gas-fired plant (11). Coal plants in the East are particularly harmful owing to their proximity to major population centers (12).

Under the assumptions used here, wind turbines in Indiana provide the greatest annual health, environmental, and climate benefits (Fig. S2)—nearly \$300/kW installed (\$100/MWh); displaced CO_2 emissions account for less than 20% of the total. By contrast, the combined benefits from the average wind turbine in California are \$32/y (\$13/MWh) and displaced CO_2 emissions account for nearly 80% of the total.

Thirty percent of existing wind capacity is installed in Texas and California (13), where the combined health, environmental, and climate benefits from wind are among the lowest in the country. Less than 5% of existing wind capacity is in Indiana, Ohio, and West Virginia, where wind energy offers the greatest social benefits from displaced pollution.

Cost-Effectiveness of the Production Tax Credit Subsidy. As of 2009, there was ∼34,000 MW of installed wind generation in the United States, producing more than 74 million MWh of electricity annually (14). Assuming a social cost of carbon dioxide of \$20 per ton and a value of a statistical life of \$6 million, we estimate that these wind farms provide \$2.6 billion in social benefits annually, equivalent to \$35/MWh (*SI Text*). The benefits are primarily from displaced SO_2 (44%) and displaced CO_2 (40%). Through the Production Tax Credit, the federal government provides a direct subsidy of \$22/MWh for wind energy. We estimate that the cost of the subsidy was \$1.6 billion in 2009. This suggests that the Production Tax Credit is a good value for taxpayers—the social benefits from existing wind farms are roughly 60% higher than the cost of the subsidy. Assuming a social cost of carbon dioxide of \$30 per ton, CO_2 reductions alone justify the cost of the tax credit for existing wind farms.

However, if health and environmental benefits are the justification, the Production Tax Credit may over- or under-subsidize wind energy depending on the location. For example, the combined health, environmental, and climate benefits from wind energy in Ohio are \$100/MWh—more than four times the subsidy—compared with only \$13/MWh in California. In addition, production-based subsidies encourage developers to seek sites with high energy output, although electricity production may not be the goal of taxpayers and policy makers.

Social Benefits of Solar Energy. Results for solar PV are shown in Fig. 1, *D–F*. Energy output from solar is highest in the Southwest and lowest in New England. A solar panel in Arizona, for example, is expected to generate ∼60% more electricity than the same panel in Maine.

For a 1-kW solar panel, the annual value of displaced CO_2 emissions ranges from \$15 in Vermont to \$30 in Kansas, equivalent to \$11/MWh and \$17/MWh. In California and the Southwest, natural gas is the dominant marginal fuel and, as a result, solar panels displace relatively little CO_2. Avoided CO_2 emissions are highest in Kansas, Nebraska, Virginia, and the Carolinas, where there is a moderate solar resource and a carbon-intensive supply of electricity. The average solar panel in Nebraska displaces 20% more CO_2 than a panel in Arizona, although energy output from the Nebraska panel is 20% less.

Solar panels in Indiana, Ohio, or West Virginia achieve significant health and environmental benefits by displacing coal-fired generators. Despite a poor solar resource, a 1-kW PV panel in Ohio provides \$105 in health and environmental benefits per year (\$75/MWh)—15 times more than the same panel in Arizona. Remarkably, if the goal is to improve air quality and human health, Arizona and New Mexico are among the worst locations for solar.

Comparison Between Wind and Solar. In most of the United States wind turbines have higher capacity factors than solar panels. As a result, a 1-MW wind turbine will offset more health, environmental, and climate damages than a 1-MW solar installation (Fig. 1). On a per-megawatt-hour basis, wind and solar energy may result in different social benefits because of temporal differences. Wind output tends to be highest late at night, when demand is low and coal is more often on the margin (15). Solar output peaks midday, when demand is high and gas is more often on the margin. As a result, a megawatt-hour of wind energy may displace more emissions than a megawatt-hour of solar energy. The difference between wind and solar, on a per-megawatt-hour bases, is negligible in much of the country. In Virginia and Maryland, where the difference is most pronounced, a megawatt-hour of wind energy results in 30% more health, environmental, and climate benefits than a megawatt-hour of solar energy.

Sensitivity Analysis. If the goal of renewables is to mitigate climate change or reduce health and environmental damages, then (*i*) the benefits of wind and solar energy vary widely depending on location, and (*ii*) the sites with the highest energy output are not necessarily the best for offsetting health and environmental impacts. These conclusions hold under a wide range of assumptions. Results are most sensitive to the value of a statistical life, the social cost of CO_2 emissions, and the dose–response function that relates mortality to concentrations of fine particulate matter (16). Changes to these assumptions affect the magnitude of our results, but the regional variations presented in Fig. 1 persist (Fig. S3). Regional variations are qualitatively consistent if we assume that wind and solar displace the average (rather than marginal) damages from electricity production (Fig. S4). This verifies that the conclusions of this analysis do not depend on the details of the regression model.

This analysis assumes that wind and solar affect only generators within the same eGRID subregion; imports and exports of electricity from neighboring regions are ignored. We can reduce, but not eliminate, the errors associated with this assumption by defining larger regions, although this may mask variations in the generation mix (17). In *SI Text* we repeat the analysis using eight regions of the North American Electric Reliability Corporation, rather than the 22 eGRID subregions (Fig. S5). We find that regional variations are qualitatively consistent.

Perhaps the most important assumption in this analysis is our treatment of displaced emissions in the eastern United States, where NO_x and SO_2 are regulated under cap-and-trade programs. If pollution caps are binding, total emissions remain fixed and wind or solar will not achieve a net reduction in SO_2 and NO_x. In such cases, "displaced" emissions can be valued using allowance prices, which reflect the avoided abatement costs for generators in the system.

If pollution caps are not binding, as assumed in Fig. 1, then wind and solar generation will reduce overall emissions, thus reducing health and environmental damages. Caps have not been binding in recent years for NO_x (2010) and SO_2 (2008 and 2009) (18). Through the Cross-State Air Pollution Rule (CSAPR), the EPA has proposed aggressively lower caps, although the future of these regulations is uncertain (18).

We have repeated our assessment of wind and solar under the assumption that CSAPR takes effect. For the eastern United States, we value displaced NO_x and SO_2 emissions using the EPA's projected allowances prices for 2014 (Table S1) (19). This approach changes the interpretation of the results—rather than measuring the health and environmental benefits of renewables, we are estimating the cost-savings of meeting the CSAPR pollution cap. For regions and pollutants unaffected by cap-and-trade regulation, we retain the original method of valuing displaced emissions using health and environmental damages.

This approach significantly lowers the estimated benefits of wind and solar in certain regions (Fig. S6). For example, in the absence of a binding cap-and-trade program, a 1-kW solar panel in Ohio is expected to yield $105 in annual benefits ($75/MWh) from displaced SO_2, NO_x, and $PM_{2.5}$ (Fig. 1*F*). With CSAPR in effect, the value falls to $20/y ($15/MWh). This difference arises because health and environmental damages from SO_2 emissions are roughly 10 times higher than allowance prices, suggesting that the proposed SO_2 cap is too lax. In economic theory, social welfare is maximized when the marginal abatement costs equal the marginal social damages for a pollutant.

Even using the CSAPR valuations, regional variations persist (Fig. S6). For example, the benefits of displaced SO_2, NO_x, and $PM_{2.5}$ for a solar panel are six times greater in New Jersey than in Arizona, although energy output from the New Jersey panel is 30% less. The details of the sensitivity analysis are presented in the *SI Text*.

Large-Scale Adoption of Wind or Solar. This analysis assumes that wind and solar displace damages from marginal electricity production. In other words, we are evaluating the benefits of a near-term, small-scale intervention. Large-scale adoption of wind or solar will, in the short term, result in deep displacements of existing generators (Fig. S7). In such cases, coal accounts for a greater share of displaced generation in most regions, resulting in even greater reductions in pollution-related damages (Fig. S8). With increased penetration of wind or solar, conventional generators may be required to cycle more often, resulting in an emissions penalty (2, 20, 21); these effects are not captured in our analysis. In the long-term, large-scale adoption of wind or solar will affect investment and retirement decisions for conventional generators. Although this may have a significant impact on emissions, a full analysis of these issues is beyond the scope of this work. The implications of large-scale interventions are discussed further in *SI Text*.

Discussion

If the goal of renewable energy is to mitigate climate change or reduce human-health impacts, then the sites with the highest energy output are not the best choice in many cases. We find that a solar panel in New Jersey displaces significantly more criteria pollutants than a panel in Arizona, resulting in 15 times more health and environmental benefits. Similarly, despite the excellent resource, a wind turbine on the plains of Montana displaces 45% less CO_2 emissions than a turbine in West Virginia. These results are driven primarily by regional variations in the generation mix: there are significantly greater benefits when wind or solar displace coal- or oil-, rather than gas-fired, generators.

We estimate that the social benefits of wind and solar are more than $40/MWh in much of the United States and as high as $100/MWh in the parts of the mid-Atlantic and Midwest (Fig. S2). This suggests that appropriately valuing health, environmental, and climate impacts would significantly improve the competitiveness of wind and solar in some regions. In places like California, given how clean the electricity mix already is, additional investments in wind and solar achieve comparatively little health and environmental benefits.

There are also regional differences in the private costs and benefits of renewable energy, which have not been considered here. Capital and labor costs, availability of transmission, and the price of electricity all vary by location. Ultimately, the "best" sites for wind and solar will depend on both private and social costs.

If emissions were priced at the level of social damages, either through a tax or cap-and-trade policy, then electricity generators and consumers would internalize those costs. Private investors would then choose locations for wind and solar installations according to the full cost of electricity, which would account for the regional differences illustrated above. However, the United States currently lacks a national policy covering CO_2 emissions, and existing cap-and-trade programs value SO_2 emissions well below the level of social damages. In the absence of more comprehensive policies, it is likely that direct subsidies for renewables will remain an important policy instrument.

We provide a first-order evaluation of the Production Tax Credit and conclude that the cost of the subsidy is justified on a national basis. We estimate that the social benefits from existing wind farms are ~60% greater than the cost of the tax credit. However, we argue that nationwide production-based subsidies are a crude policy instrument because they fail to reflect regional differences in the health, environmental, and climate benefits of renewables. Per megawatt-hour, wind energy in Ohio offers five times more social benefits than wind energy in New Mexico, yet the two receive the same subsidy under the Production Tax Credit. In addition, production-based subsidies encourage private developers to seek sites offering high energy output, although, as this analysis has shown, energy output is poorly aligned with health and environmental benefits.

Materials and Methods

To evaluate the social benefits of wind and solar, we (*i*) gather emissions data for more than 1,400 fossil-fueled power plants, (*ii*) estimate the health, environmental, and climate damages from those emissions, (*iii*) use regressions of hourly emissions and generation data from 2009 through 2011 to estimate the damages from marginal electricity production by region, and (*iv*) estimate the reduction in damages that occurs when conventional generators are displaced by wind or solar. Each step is discussed below.

Emissions Data. Hourly emissions data from 2009 through 2011 are from the EPA's Continuous Emissions Monitoring System (CEMS) (22). CEMS data include generator-level SO_2, NO_x, and CO_2 emissions, as well as gross power output for fossil-fueled generators greater than 25 MW (23). We assume that nuclear, hydroelectric, and other generators that are excluded from the CEMS database do not operate on the margin. Because nuclear provides base-load power and hydroelectric has a very low marginal cost, neither generation source is likely to be displaced by wind or solar. This assumption is discussed further by Siler-Evans et al. (15).

Annual $PM_{2.5}$ emissions data by power plant are from the 2005 National Emissions Inventory (24). We assume that emissions are proportional to power output, allowing us to estimate hourly $PM_{2.5}$ emissions. We divide the annual $PM_{2.5}$ emissions by the annual electricity produced, giving an emissions rate for each plant. We then multiply the emissions rate by the hourly power output (using CEMS data), which gives the hourly $PM_{2.5}$ emissions from each fossil-fueled plant in the dataset. This analysis does not account for life cycle emissions associated with constructing power plants or extracting or delivering fuels. Plant locations and primary fuel types are from the EPA's eGRID database (14).

Damages from Criteria Pollutants. Damages from criteria pollutants are from the APEEP model (8), which was recently used by the National Research Council to estimate the externalities from electricity production (11). APEEP estimates the damages from emissions of SO_2, NO_x, $PM_{2.5}$, coarse particulate matter (PM_{10}), volatile organic compounds (VOC), and ammonia (NH_3) on a dollar-per-ton basis (8, 10, 16). Damages include human-health effects (e.g., lung cancer, bronchitis, asthma, and cardiopulmonary diseases), reduced crop and timber yields, reduced visibility, degradation of materials, and lost recreational services.

For each source location, APEEP uses a Gaussian plume model to estimate the dispersion of emissions and the resulting concentrations in each county. Dose–response functions are used to estimate physical effects to populations and other receptors (crops, forests, materials, etc.). Physical effects are translated to monetary values using market prices for lost commodities, costs of illnesses, and nonmarket valuations from the literature. Monetized damages are driven largely by the value placed on premature deaths from air pollution. The damage estimates used here value mortality at $6 million (11, 25).

Results from the APEEP model give the average, dollar-per-ton damages for each pollutant (SO_2, NO_x, $PM_{2.5}$, PM_{10}, VOC_s, and NH_3) emitted in each US county. APEEP provides separate damage estimates for point sources with low, medium, and high effective stack heights (11). We assume a medium effective stack height (250–500 m) for all power plants. For each plant, we multiply hourly emissions by the dollar-per-ton damage value for the appropriate county. The result is hourly damages for each pollutant from 2009 through 2011 for more than 1,400 fossil-fueled power plants. VOCs, NH_3, and PM_{10} are excluded from this analysis because they result in damages that are, on average, more than two orders of magnitude lower than damages from other pollutants.

Damages from CO_2 Emissions. There have been various attempts to estimate the cost of damages arising from CO_2 emissions, often termed the social cost of carbon dioxide. The Intergovernmental Panel on Climate Change and the National Research Council report values that range from $0 to more than $100 per ton of CO_2 (11, 26). Using a range of assumptions, the US Interagency Working Group on Social Cost of Carbon estimates damages of $5, $21, $35, and $65 per ton of CO_2 emitted in 2010 (in 2007 dollars) (27). From 2005 through 2009, the price per ton for CO_2 allowances in the European Union trading market averaged roughly €20 (28). More recently it has fallen to less than half of that (29). In light of this varied evidence, we adopt a social cost of carbon dioxide of $20 per ton.

For each power plant, we multiply the hourly CO_2 emissions by its social cost to find the hourly damages from 2009 through 2011. Results are linearly related to the social cost, so doubling (or halving) the assumed cost doubles (or halves) the damages resulting from CO_2 emissions.

Estimating Marginal Damages from Electricity Production. Hourly damages from power plants are aggregated by eGRID subregions, giving a vector of hourly damages for 22 regions and four pollutants (SO_2, NO_x, $PM_{2.5}$, and CO_2). Similarly, we aggregate hourly gross generation from fossil-fueled power plants in each region. We then calculate the change in total fossil generation (G) and change in damages (D) between one hour (h) and the next for each eGRID subregion (r) and each pollutant (p):

$$\Delta G_{r,h} = G_{r,h+1} - G_{r,h}(\text{MWh}) \qquad \Delta D_{r,p,h} = D_{r,p,h+1} - D_{r,p,h}(\$)$$

Using hourly data from 2009 through 2011, there are more than 25,000 observed changes in damages corresponding to a change in generation for each region and each pollutant. A linear, ordinary least-squares regression of ΔD on ΔG estimates the marginal damages from electricity production (β, in dollars per megawatt-hour) for each region and each pollutant:

$$\Delta D_{r,p} = \beta_{r,p} \times \Delta G_r + \text{Intercept} + \varepsilon$$

To account for temporal variations, data are binned according to the level of system demand, which is a strong predictor of the marginal emissions rates of an electricity system (15, 30). We used total fossil generation (based on CEMS data) as a proxy for system demand. Hourly data are binned by every fifth percentile, where the first bin contains the 5% of data occurring during the lowest-demand hours, and the 20th bin contains the 5% of data occurring during the highest-demand hours. Fig. 2*A* shows an example of this method for SO_2 emissions in the Texas electricity system, known as the Electric Reliability Council of Texas (ERCOT). During low-demand hours (bottom 5%), displacing a megawatt-hour of electricity is expected to reduce $19 in damages from SO_2 emissions. Displacing electricity has a negligible effect on SO_2 during high-demand hours (top 5%), when gas-fired generators are on the margin (15). For each pollutant, separate regressions are used to calculate marginal damages using data within each bin. Example results from these regressions are shown in Fig. 2*B* for the ERCOT region (Texas). Damages from marginal electricity production are highest when demand is low and coal is more often on the margin. As demand increases, marginal damages tend to decrease as gas accounts for a larger share of marginal generation. At peak demand, NO_x emissions increase owing to the use of older gas-fired peaking plants (15). Regression results for all bins, regions, and pollutants are available online (http://cedmcenter.org/tools-for-cedm/marginal-emissions-factors-repository/).

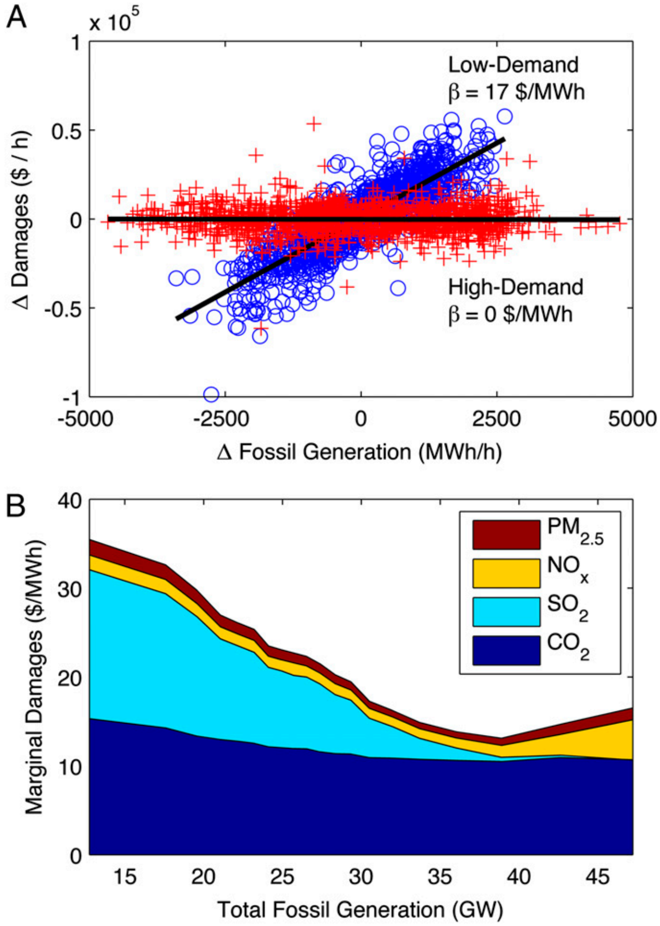

Fig. 2. Example method for calculating marginal damages from electricity generation. (*A*) Regressions for low- and high-demand hours for SO_2 and (*B*) marginal damages as a function of total fossil generation, a proxy for system demand. Both figures are based on hourly data from 2009 through 2011 for the ERCOT region (Texas).

By disaggregating the data in this way, we account for temporal variations in the electricity system. However, dollar-per-ton damages from the APEEP model are not temporally differentiated. In some cases there are seasonal differences in the effects of pollutants. NO_x is more likely to cause ground-level ozone in the summer, resulting in higher damages. Seasonal differences are accounted for in the APEEP model but are rolled into an annual-average damage value (10).

Note that we treat each region independently. Errors arise because imports and exports between regions are ignored. Larger regions would reduce these errors but may mask variations in the generation mix (9, 17). We have verified that our conclusions hold when using a coarser level of aggregation (*SI Text*).

Evaluating Wind and Solar. We evaluate wind turbines at more than 33,000 locations across the United States (Fig. S1). Wind data for 2006 are from the Eastern Wind Integration and Transmissions Study and the Western Wind and Solar Integration Study, which model wind power output from Vestas V90-3.0-MW turbines (31, 32). Wind power output data are available at 10-min temporal resolution, which we average to find the hourly power output for each site.

Similarly, we evaluate a PV solar panel at more than 900 locations across the United States (Fig. S1). Solar insolation data for a "typical meteorological year" are from the National Solar Radiation Database, which provides hourly solar intensities (33). Solar panels are assumed to have a nameplate capacity of 1 kW and an efficiency of 13%. Panels are installed facing true south with a tilt equal to the latitude of the installation site. Under these assumptions, we calculate hourly energy output for a solar panel at each location.

There are year-to-year differences in renewable resources (34), which are not captured in this analysis. We assume that wind and solar output from the single sample year repeat in future years.

To estimate the avoided damages for each wind turbine and solar panel, we determine the displaced energy in a given hour and estimate the avoided damages according to the level of fossil generation at that hour. For example, consider a wind turbine in Texas that produces 2 MWh between midnight and 1:00 AM on January 1, 2009. During this hour, total fossil generation in the ERCOT region was 21 GW, and the marginal damages from criteria pollutants and CO_2 emissions were \$16/MWh and \$13/MWh (Fig. 2*B*). Thus, the wind turbine provides \$32 in benefits from displaced SO_2, NO_x, and $PM_{2.5}$ emissions and \$26 in benefits from displaced CO_2 emissions. The process is repeated for each hour of the year from 2009 through 2011. Hourly avoided damages from the three years are summed and divided by three to find the annual effects of the wind turbine. This process is repeated for each wind turbine and solar panel. Results are presented using heat maps, which are based on an interpolation between the evaluated sites. Although we often discuss state-level results to improve readability, all health, environmental, and climate benefits are calculated using eGRID subregions. For example, a comparison of solar panels in Arizona and Ohio is based on the average impacts of all panels in those states, where impacts for each panel are calculated using regressions from the relevant eGRID subregions.

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