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Climate and health benefits of increasing renewable energy deployment in the United States*

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Abstract

The type, size, and location of renewable energy (RE) deployment dramatically affects benefits to climate and health. Here, we develop a ten-region model to assess the magnitude of health and climate benefits across the US. We then use this model to assess the benefits of deploying varying capacities of wind, utility-scale solar photovoltaics (PV), and rooftop solar PV in different regions in the US—a total of 284 different scenarios. Total benefits ranged from $2.2 trillion for 3000 MW of wind in the Upper Midwest to $4.2 million for 100 MW of wind in California. Total benefits and highest cost effectiveness for CO2 reduction were generally highest for RE deployment in the Upper Midwest and Great Lakes and Mid-Atlantic US and lowest in California. Health was a substantial portion of total benefits in nearly all regions of the US. Benefits were sensitive to methane leakage throughout the gas supply chain.

Introduction

Use of fossil fuels contributes to climate change and health impacts of air pollution [1–5]. Electricity generation is a major source of CO2, one of the main greenhouse gases (GHGs) driving climate change. Electricity is also a major source of air pollutants that harm health—sulfur dioxide (SO2), nitrogen oxides (NOx), and fine particulate matter (PM2.5) [6]. In 2017, electricity generation was responsible for 1,941.4 million metric tons (MMT) of SO2 emissions, 29.5% of GHG emissions in the United States [7]. In 2014, US electrical generation was also responsible for 68% of SO2 emissions, 12% of NOx emissions, and 3.4% of primary PM2.5 emissions [6]. Emissions from electricity generation were responsible for 31,000 excess deaths in the US in 2010 [5]. Deploying renewable energy (RE) generation is one of many strategies that can reduce reliance on fossil fuels, prevent emissions of GHGs, and reduce the health burden and other environmental impacts of electricity generation [8–11].

The climate and health benefits of the growth in RE has been assessed historically [12], marginal benefits of incremental increases have been assessed for past years [13], and the benefits of either specific project types or projects in specific regions has been assessed [9, 10, 12, 14, 15]. To build on this, we evaluate a series of RE projects at different sizes and across all regions of the US for the year 2017, using consistent methods to estimate benefits, and using health benefit modeling that incorporates seasonal differences in health impacts of emissions.

To do this, we developed the Environmental Policy Simulation Tool for Electrical Grid Interventions, v2.0, (EPSTEIN 2.0), a model to estimate health and climate benefits of RE projects, throughout the US EPSTEIN 2.0 builds on EPSTEIN 1.0, which was geographically limited to the Mid-Atlantic US [9]. We use EPSTEIN 2.0 to simulate the benefits of wind, utility scale solar PV, and rooftop solar PV, deployed at a variety of sizes, in 10 different regions of the US (figure S1), and evaluate and rank different RE types and locations in terms of health benefits, CO2 avoided, and

* Strategic deployment of #wind and #solar can maximize carbon reductions and health gains.

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cost per ton of CO₂ avoided with and without health benefits included.

**Methods**

Similar to EPSTEIN 1.0 [9], EPSTEIN 2.0 is an electrical grid model simulating how RE deployment affects operation of other power plants on the grid and their CO₂, NOₓ, SO₂, and PM₂.₅ emissions. This is linked to a public health impact assessment model for NOₓ, SO₂, and PM₂.₅ emissions, and a method to value the impact of GHG emissions [16, 17]. For the electrical grid model, EPSTEIN 2.0 uses the Avoided Emissions and Generation Tool (AVERT), an intermediate-complexity electrical grid simulation model produced by the US Environmental Protection Agency (EPA) [18]. To value the benefits of reduced CO₂ emissions, EPSTEIN 2.0 uses the US regulatory social cost of carbon (SCC) [19, 20]; to value the health benefits of reduced SO₂, NOₓ, and PM₂.₅ emissions, EPSTEIN 2.0 uses a reduced complexity health benefits assessment model, Estimating Air Pollution Social Impacts Using Regression (EASIUR) [16, 21, 22]. In all cases, dollar values from valuation methods are expressed in 2017 USD (figure 1).

We developed a series of scenarios (table S1, figure 1), modeling the effects of increasing wind, utility solar PV, or rooftop solar PV in the year 2017. We used increments of 100, 300, 400, 500, 1000, 1500, 2000, 2500, and 3000 MW in each region of the US, with some regions having an additional run at 200 MW, and ran each scenario individually. We then rank the different location and energy type combinations in terms of climate benefits and health benefits and calculate health benefits per CO₂ reduction for each region and energy type. We decompose benefits of each scenario by displaced plant primary fuel type, emissions, and benefits per MWh of RE generated. We also assess the sensitivity of results to methane leakage from the natural gas system. Each component of the model and the other analyses are described below.

**AVERT electrical grid model**

AVERT is an intermediate complexity electrical grid model, designed to estimate the benefits of increased RE deployment and energy efficiency [18]. It uses historical hourly power plant generation and emissions data for each individual power plant to predict the response of individual power plants to changes in electrical demand for a given year, based on the performance (emissions rates, pollutant control status, boiler status, permitting, and other applicable policies) of each individual plant in that year [18]. AVERT splits the continental US into ten regions, corresponding to the major electrical grid regions (figure S1). We use prototypical capacity profiles from within AVERT for renewables in each region developed from wind and insolation data on a sampling of sites in each region [18, 23–25]. AVERT is less complex than more sophisticated electrical grid models that use grid economics, production cost, and operational and transmission constraints to simulate power plant behavior [18]; however, more sophisticated models are often proprietary and computationally intensive [18]. We compare output from AVERT to previous work using Ventyx/PROSYM, a complex economic simulation electrical dispatch model [9].
The output from AVERT includes changes in generation, fuel consumption, and emissions of CO$_2$, NO$_x$, SO$_2$, and PM$_{2.5}$, on both annual and monthly timescales, for each plant on the grid where RE is deployed. In about half of the regions, the high capacity scenarios resulted in displacement of more than 15% of fossil generation, a threshold within AVERT where results may have decreased reliability (table S1).

To compare results from EPSTEIN 2.0 to results from EPSTEIN 1.0, we perform one run with 500 MW of wind and one with 500 MW of utility solar PV for 2012, the model year for the EPSTEIN 1.0 simulations [9].

**Estimating benefits of emissions reductions**

EPSTEIN 2.0 estimates benefits from reducing CO$_2$ emissions using the SCC [20]. The SCC is derived from impact assessment models that capture, in monetary terms, the impact of emitting one extra ton of CO$_2$ [20]. The SCC captures some health impacts of climate change, agricultural productivity impacts, property damage, and impacts on ecosystem services [20]. Our main SCC estimate is $41.80/short$ ton CO$_2$, $112/short$ ton CO$_2$ (high impact scenario, 3% discount rate) is our high SCC estimate, and a low of $12/short$ ton [20].

We use EASIUR to estimate the total benefits of reduced emissions of SO$_2$, NO$_x$, and PM$_{2.5}$, including health benefits occurring outside the region where emissions reductions are occurring [16, 21, 22]. Details of EASIUR are available elsewhere, [16, 21, 22], but briefly, EASIUR is constructed from a series of 100 runs using the Comprehensive Air Quality Model with Extensions (CAMx), a complex atmospheric chemistry, fate, and transport model. These runs simulate the impact of an additional ton of emitted pollutant in a location on PM$_{2.5}$ levels in all areas downwind. This model output was then used to create a generalized model for air quality impacts, population exposure, and health impacts, using US Census and Centers for Disease Control data from the Benefits Mapping and Analysis Program (BenMAP), and existing literature on health impacts of PM$_{2.5}$ [16, 21, 22, 26, 27]. EASIUR provides monetized estimates of health impacts of emissions occurring on a 36 km × 36 km grid at three different heights, both averaged throughout the year and seasonally. We primarily use the seasonal values of from EASIUR linked to monthly output from AVERT, but compare these results to those obtained using the annual average values from EASIUR.

We adjust the direct output from EASIUR to reflect a concentration-response curve with a slope of 1.29% (95% CI: 1.09–1.50), from a meta-analysis of 53 studies of the relationship between mortality risk and annual average PM$_{2.5}$ exposure [28]. Decreases in

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**Figure 2.** Benefits per MWh of renewable energy deployed for each electrical grid region in the US Benefits are shown for wind, rooftop solar, and utility solar PV, and broken down by pollutant type displaced.
mortality risk are valued using the value of statistical life (VSL), an estimate of willingness to pay for reduced mortality risk [29, 30]. The VSL is commonly used in regulatory impact analyses, and in environmental health policy research to value health benefits from reducing air pollution [9, 10, 12, 31, 32]. Here, we use a VSL of $11.2 million, corresponding to the central estimate of the VSL, adjusted for inflation and income growth [29, 30]. We then present these results in terms of benefits per MWh and health benefits per ton of CO$_2$ reduced. We also rank each type and location in terms of cost per ton of CO$_2$ reduced, with and without health benefits.

To examine what drives variability in benefits between different scenarios, we break the model results into its component parts—grouping scenarios by RE type and location and then determining the rate of benefits per MWh generated. For each region and RE type combination, we examine primary fuel types of the plants displaced, emissions displaced, and benefits across regions and RE types.

We also examine the sensitivity of these results to methane leakage, assuming that leakage rate scales linearly with gas consumed—an approach common in attributional life cycle assessment [33]. We estimate methane leakage rate from the fossil gas supply chain using an estimated 2.3% leakage in the gas transmission system [34], and a methane loss rate from power plants of 0.26%, the middle of the range of estimated leakage rates from power plants [35]. We estimate the mass of methane leaked using a heating value of 1037 Btu/ft$^3$, a density of 0.05 lb/ft$^3$, and gas with a 95% methane content. We value the cost of this leakage using the US EPA social cost of methane.

Figure 3. (a) Mid (point), and high and low (whiskers) estimates of total benefits per MWh for each RE type and location. Middle estimates are represented by points, with low and high represented by error bars. (b) Mid (point), and high and low (whiskers) estimates of health and climate benefits per MWh for each RE type and location. Middle estimates are represented by points, with low and high represented by error bars. (c) Mid (point), and high and low (whiskers) estimates of benefits per MWh for each RE type and location, for CO$_2$, NO$_x$, SO$_2$, and PM$_{2.5}$ emissions reduced. Middle estimates are represented by points, with low and high represented by error bars.
($1296/\text{metric ton, after adjusting for inflation}) [20], and a separate estimate that includes health impacts ($4404/\text{metric ton, after adjusting for inflation}) [36].

**Results**

**Health and climate benefits of RE**

The total benefits of RE varied dramatically across scenarios—with central estimates ranging from $4.2 million for 100 MW of wind in California, to $1.2 trillion in benefits from installing 3000 MW of wind in the Upper Midwest. Across all parameter choices and scenarios, the benefits ranged from $1.7 million for installing 100 MW of wind in California, to $2.2 trillion for 3000 MW of wind in the Upper Midwest, using high values for the effects of PM\textsubscript{2.5} on mortality, and the highest value of the SCC. Incorporation of season had modest effect on the benefits estimates—generally increasing benefits for wind and decreasing them for solar, except in the Northeast (figure S2). The rate of benefits generated per MWh of renewable electricity generated were quite similar within each region and RE type (figures S3 and S4). This indicates that, as modeled by EPSTEIN 2.0, the relationship between RE generated and social benefits is essentially linear, for each region and each RE type. Since this rate is essentially linear, we use the benefits rates per MWh of RE to examine trends between RE types and regions, along with the drivers behind this variation. We use the mid-range values for the SCC, VSL, and the estimate of the relationship between annual average PM\textsubscript{2.5} exposure and increased mortality risks through-out, unless otherwise stated.

The total benefits per MWh varied by a factor of 4 between regions and RE types, ranging from $28 per MWh for Wind in California, to $113 per MWh for wind in the Upper Midwest and Utility Solar PV in the Great Lakes. Within a given region, the benefits per MWh of different RE types were fairly similar (figures 2, 3, and S5). For both solar PV types, the Great Lakes/Mid-Atlantic (referred to as ‘Great Lakes’...
throughout) had the highest benefits per MWh, followed by the Upper Midwest, and then the Lower Midwest (figures 2 and 3). The lowest three were California, followed by the Southwest, and then the Rocky Mountains (figures 2 and 3). For wind, the highest three were the Upper Midwest, followed by the Great Lakes, and then the Lower Midwest; the lowest three were California, the Southwest, and the Rocky Mountains (figures 2 and 3). For 2012 in the Great Lakes region, the total benefits per MWh hour were roughly double that of our 2017 analyses (table S2). This is largely driven by 2017 having much lower benefits from SO2 reductions compared to 2012, reflecting RE displacing proportionately more gas and less coal in 2017 than in 2012.

Health benefits vary much more than climate benefits (figure 3). Regions in the eastern half of the US generally had higher health benefits and higher total benefits than regions in the western half. Regions with a higher proportion of coal displaced tended to have higher health benefits and total benefits (figure 4). These trends were fairly consistent across RE types, but the trends and the exact ranking of regions are somewhat sensitive to parameter choice.

**Deployment of RE to optimize climate and health benefits**

Separating the health benefits from the climate benefits reveals a ranking of regions and RE types, agnostic to different values of health and climate benefits—basically providing the ‘efficiency frontier’ of health and climate benefits (figures 5(a) and (b)) [37]. The majority of variation is between regions; the benefits per MWh of different RE types generally cluster by region (figures 5(a) and (b)). RE deployment has the greatest CO2 reductions in the Upper Midwest, closely followed by the Lower Midwest (figures 5(a) and (b)). The highest health benefits from deploying more RE occur in the Great Lakes, followed by the Upper Midwest, and then the Lower Midwest (figure 5(a)). Examining health benefits per CO2 reduction instead of per MWh reveals a slightly different ranking. The

![Figure 3](Continued.)
Great Lakes and Upper Midwest are still first and second, but the Northeast moves to third (figures 5(b) and 56).

Variation in benefits between different regions and types of RE can be explained by differences in primary fuel types displaced, emissions displaced, and benefits per emission reduction. Coal and gas were the predominant primary fuel types displaced; small amounts of oil were displaced in the Northeast, the Lower Midwest, and the Great Lakes; and small amounts of other fuel types (this can include waste-derived fuel and waste gases) were displaced in California and the Great Lakes (figure 4). The highest amounts of coal were displaced in the Great Lakes, Upper Midwest, Lower Midwest and Rocky Mountains (figure 4). These regions also generally tended to have higher climate and health benefits, but with varying contributions from each emission type (figure 6).

Valuing reduced methane leakage from gas usage using the Shindell et al social cost estimate [36] increased the total benefits per MWh of RE by a mean of ~36% (range: 17%–66%); using our low estimate, the total benefits per MWh increased by a mean of ~11% (range: 5%–19%) [20]. Comparing just the contribution of methane leaks to the total benefits of reducing gas consumption increased the benefits of reducing gas consumption by ~71% (range: 43%–87%); using our low estimate of the social cost of methane increased the benefits of reducing gas consumption by 21% (range: 13%–25%).

Regions with high amounts of CO₂ emissions avoided with RE deployment generally have much lower costs per ton of CO₂ reduced (figure 7). Wind and utility-scale solar PV have fairly similar costs per MWh, so have fairly low cost per ton of CO₂ reduced. Costs per ton of CO₂ reduced for rooftop solar are much higher, reflecting a higher cost per MWh of rooftop solar [38]. Wind and utility solar PV have lower costs per ton of CO₂ reduced in the Upper Midwest, Lower Midwest, Rocky Mountains, and the Great Lakes. When the health benefits of RE are subtracted from the cost, the cost drop substantially. This also rearranges the ranking somewhat—the Upper Midwest, Great Lakes, Upper Midwest, and Southeast then get the lowest cost per ton of CO₂ avoided (figure 7).

**Discussion**

Here, we developed EPSTEIN 2.0, and used it to estimate the climate and health benefits for RE in 10 grid regions across the US for different sizes and types of RE deployment in each region. Benefits scaled roughly linearly with the size of the RE project deployed, and differences between regions were much greater than the differences between RE types.
Deploying RE has benefits to both climate and health everywhere in the US, and the magnitude of each depends on the fuel types reduced, emissions reductions, and benefits of emissions reductions. Benefits vary by location and are quite sensitive to different parameter values. The Great Lakes and the Upper Midwest generally have the highest benefits, followed by the Lower Midwest, largely due to coal displacement and the populations downwind. The Northwest and Rocky Mountains have high climate benefits, largely due to coal displacement. The Northeast has fairly high health benefits per ton of CO2 reduced, largely driven by reduced use of gas and oil in a region with high population density.

Variations in benefits reflects differences in the primary fuel types of plants displaced, emissions reduced, and health benefits of those emissions reductions. For example, wind in the Upper Midwest has higher benefits than the Great Lakes. However, for both types of solar, the Great Lakes has higher benefits than the Upper Midwest, largely driven by SO2 reductions (figure 3(c)). This difference in SO2 reductions from solar largely results from differences in displacement of coal and other fuels (figure 6). This reflects coal in the Great Lakes having higher impacts per MWh than coal in the Upper Midwest (figure S7), largely due to higher emissions rates from plants displaced in the Great Lakes (figure S8).

The results here are similar to results of studies focused on other regions [9–11, 13, 14], and to a historical reconstruction of the benefits of RE [12]. However, there are some differences between studies using more sophisticated electrical dispatch modeling. One study focused on offshore wind found that the benefits of wind did not scale linearly with the amount of capacity deployed [10]. This is likely due to that dispatch...
model being better able to capture plant specific responses to offshore wind going into operation, resulting in non-linearities at grid-scale. A study focusing in detail on the PJM Interconnection, which substantially overlaps with the Great Lakes/Mid-Atlantic region in AVERT, and using 2012 as a simulation year, did find that different locations of RE deployment within the same region had substantially different benefits. This demonstrates advantages of the more sophisticated electrical dispatch modeling and of using higher resolution data on available wind and solar resources, since the results here did not match this previous study in locations where solar had a lower capacity factor.

There are a number of limitations with EPSTEIN 2.0. AVERT does not capture the degree of detail that other electrical grid models can capture, including plant upgrades and retirements, changes in response from changes in fuel prices, transmission upgrades, policy changes, pollutant control status, market changes, changes due to fuel mixing, and other factors that may make historical responses not represent the present. AVERT may also miss grid dynamics that more elaborate electrical dispatch modeling captures, resulting in some uncertainty in responses in individual plants. EASIUR does not capture ozone or morbidity endpoints due to either PM$_{2.5}$ or ozone, therefore underestimates total benefits. This model assigns emissions reductions and consequent benefits to plant primary fuel type, rather than literal fuel displaced. Therefore, it does not disaggregate benefits of reduced fuels in plants that use multiple fuel types. The model framework also does not capture benefits across the life cycle of reduced coal or gas consumption. Health impacts of coal mining can make up a substantial portion of the total impacts of coal [39–41]. Health impacts related to proximity to natural gas wells were not included here [42–44]. Assessing the impacts of stack emissions from power plants, as in our main analysis, substantially underestimates...
the total benefits from RE, by omitting the benefits of reducing consumption of fossil fuels. Our results indicate that including methane leakage in the natural gas supply chain alone can increase benefits by 36%.

Including carbon emissions reductions and health benefits in RE planning

Deploying RE in different locations can have substantially different benefits, and the cost per ton of CO₂ avoided varies substantially depending on the location where RE is installed (figure 7). While health benefits of RE deployment tend to be high in areas that also have high CO₂ reduction potential, there can be tradeoffs between CO₂ reductions and health benefits.

For example, deploying RE in the Rocky Mountains has roughly the same CO₂ reduction potential as the Great Lakes, but much lower health benefits (figures 5(a) and S5). Comparing strictly in terms of cost per ton of CO₂ reduced, deploying wind and utility-scale solar PV anywhere in the US is more cost effective than deploying live air carbon capture and sequestration (CCS) (figure 7) [45]. Deploying wind and utility-scale solar PV in many regions of the country is also more cost effective than installing CCS on a coal-fired power plant (figure 7) [38].

Health benefits can be an important part of benefit cost assessments of carbon mitigation. For example, deploying wind or utility-scale solar PV in all regions of the country, except the Southwest and California, is more cost effective than installing CCS on a coal-fired power plant when including health benefits (figure 7). Wind and utility scale solar deployed anywhere, along with rooftop solar in the Upper Midwest and the Great Lakes, are more cost effective at reducing CO₂ than deploying live air CCS when health is included (figure 7).

Our model results, along with CO₂ reduction cost-effectiveness, do not represent full benefit-cost analyses of individual projects. Ideally, a full benefit-cost analysis for an individual project would include: site specific generation profiles and detailed electrical dispatch model runs for RE; full health benefits and
impacts of emissions changes from coal with CCS [39, 46, 47]; full life cycle impacts for fossil fuel use changes, including increases in the case of coal with CCS [39, 48–50]; impacts of captured CO₂, especially if it is used for enhanced oil recovery [45, 51]; electricity price effects [52, 53], and impacts from RE manufacture and installation [54–57].

This model framework and information can be useful for governments, RE developers, and investors for developing RE deployment strategies that maximize both CO₂ reductions and health benefits. It can also be used to estimate CO₂ reductions from renewable energy credits (RECs), power purchase agreements (PPAs), and increases in renewable portfolio standards (RPS). It allows governments to evaluate the health benefits of RPS increases and allows for REC and PPA purchasers to evaluate their CO₂ reductions and health benefits. This framework allows RE developers or purchasers of PPAs or RECs in the US better understand the environmental benefits of different options. With this framework, siting or purchasing decisions could be based on health benefits, CO₂ emission avoided, or a mixture of the two. Estimates of the CO₂ reductions from a PPA or a REC could allow for these to be purchased as a form of carbon offset and could even be used to create health impact offsets.

Our results show that RE deployment is a cost-effective method to reduce CO₂ emissions, and that health benefits can be an important component of the full benefits of RE projects. We show that with the current electrical grid, in most locations, RE deployment is more cost effective at reducing CO₂ emissions than live air CCS or coal with CCS. Cost effectiveness varies substantially by region where the RE type is deployed but varies less between type of RE. We also demonstrate that health impacts and benefits of these different CO₂ reduction strategies can be a substantial part of the total.

Figure 7. Ranked cost of reducing or removing CO₂ per ton, based on low and high levelized cost of energy for each renewable energy type [38], with and without health benefits subtracted from cost. Illustrative costs of live air carbon capture and sequestration (LA CCS) [45], and coal with carbon capture sequestration [61] are added for comparison. The thinly dashed line marks a social cost of carbon of $41.80 per metric ton, and the thick and thin dashed line marks a social cost of carbon of $112.2 per metric ton.
impacts, costs, and benefits of a given project. The sensitivity to methane leakage from the gas system indicates that life cycle considerations could be important. Our work demonstrates that assessing health benefits can be included in evaluating RE deployment, and possibly other types of climate policies as well [58]. Information on health benefits is often quite informative to the public discussion and to decision-making and can be useful in both building political support for climate policies and ensuring that they are healthy and just [9, 59, 60].

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Any data that support the findings of this study are included within the article. Supplementary material for this article can be found at stacks.iop.org/ERL/14/114010/mmedia

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References

[1] Watts N et al 2018 The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come Lancet 392 2479–514
[2] Watts N et al 2018 The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health Lancet 391 581–630
[3] Rasworth K 2017 Comment A doughnut for the anthropocene: humanity’s compass in the 21st century Lancet Planet. Health 1 e48–9
[4] Stanaway JD et al 2018 Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017 Lancet 392 1925–94
[5] Lelieveld J, Evans J S, Finnis M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale Nature 525 367–71
[6] US Environmental Protection Agency. National Emissions Inventory
[7] US EPA OCPPD 2019 Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2017 Report Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2017 (Washington, DC: USEPA) pp 1–675
[8] Jacobson M Z et al 2017 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 Countries of the World Joule 1 108–21
[9] Buonocore J J et al 2015 Health and climate benefits of different energy-efficiency and renewable energy choices Nat. Clim. Change 6 100–5
[10] Buonocore J J, Luckow P, Fisher J, Kempton W and Levy JI 2016 Health and climate benefits of offshore wind facilities in the Mid-Atlantic United States Environ. Res. Lett. 11 1–11
[11] Abel DD et al 2018 Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: an interdisciplinary modeling study PLoS Med. 15 e1002599
[12] Millstein D, Wiser R, Bolinger M and Barbose G 2017 The climate and air-quality benefits of wind and solar power in the United States Nat. Energy 2 17134
[13] Siler-Evans K, Azevedo IL, Morgan MG and Apt J 2013 Regional variations in the health, environmental, and climate benefits of wind and solar generation Proc. Natl Acad. Sci. USA 110 11768–73
[14] Abel D et al 2018 Potential air quality benefits from increased solar photovoltaic electricity generation in the Eastern United States Atmos. Environ. 175 62–71
[15] Wiser R et al 2016 Long-term implications of sustained wind power growth in the United States: potential benefits and secondary impacts Appl. Energy 179 146–58
[16] Heo J, Adams P J and Gao HO 2016 Reduced-form modeling of public health impacts of inorganic PM2.5 and precursor emissions Atmos. Environ. 137 80–9
[17] OMB 2015 Technical Support Document: technical Update of the Social Cost of Carbon for Regulatory Impact Analysis—Under Executive Order 12866 pp 1–21
[18] US EPA OCPPPD 2018 AVoided Emissions and generation Tool (AVERT) pp 1–95
[19] Interagency Working Group on Social Cost of Carbon, US Government 2010 Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (February 2010) pp 1–51
[20] US EPA OCPPD 2016 Technical support document: technical update of the social cost of carbon for regulatory impact analysis —Under Executive Order 12866 (August 2016) pp 1–35
[21] Heo J, Adams P J and Gao HO 2017 Public health costs accounting of inorganic PM2.5 pollution in metropolitan areas of the United States using a risk-based source–receptor model Environ. Int. 106 119–26
[22] Heo J, Adams P J and Gao HO 2016 Public Health Costs of Primary PM 2.5 and Inorganic PM 2.5 Precursor Emissions in the United States Environ. Sci. Technol. 50 6601–70
[23] National Renewable Energy Laboratory. PVWatts (https://pivatts.nrel.gov)
[24] AWS Truepower. AWS Truepower (https://aws-dewi.ul.com)
[25] Vestas Wind Systems AS. 3 MW Platform 3 June 2013 pp 1–16
[26] Abt Associates Inc. BenMAP User’s Manual Appendices 16 August 2010 pp 1–438
[27] CDC. CDC Wonder. 7 December 2015 pp 1–1
[28] Vodonos A, Awad Y A and Schwartz J 2018 The concentration-response between long-term PM2.5 exposure and mortality: A meta-regression approach Environ. Res. 166 677–89
[29] Simon N B, Dockins C, Maguire K B, Newbold SC, Krupickn A J and Taylor L O 2019 What’s in a Name? A Search for Alternatives to ‘VSL’. Rev. Environ. Econ. Policy 28 213–8
[30] Dockins C, Maguire K, Simon N and Sullivan M 2004 Value of Statistical Life Analysis and Environmental Policy: A White Paper, pp 1–25
[31] Buonocore JJ, Lambert K F, Burtraw D, Sekar S and Driscoll C T 2016 An analysis of costs and health co-benefits for a U.S. Power Plant Carbon Standard PLoS One 11 e0156308–11
[32] U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Air Quality Assessment Division. Regulatory Impact Analysis for the Clean Power Plan Final Rule, 2015 Oct 20; 1–343
[33] Gilbert A Q and Sovacool B K 2018 Carbon pathways in the global gas market: an attributional lifecycle assessment of the climate impacts of liquefied natural gas exports from the United States to Asia Energy Policy 120 635–43
[34] Alvarez R A et al 2018 Assessment of methane emissions from the US oil and gas supply chain Sci. Am. Assoc. Adv. Sci. 361 186–8
[35] Lavoie T N et al 2017 Assessing the methane emissions from natural gas-fired power plants and oil refineries Environ. Sci. Technol. 51 3373–81
[36] Shindell D T, Fuglestvedt J S and Collins W J 2017 The social cost of methane: theory and applications Faraday Discuss. 200 429–51
[37] Bagdon B A, Huang C-H, Dewhurst S and Meador A S N 2017 Climate change constrains the efficiency frontier when managing forests to reduce fire severity and maximize carbon storage Ecol. Econ. 140 201–14
[38] Lazard Lazard’s Levelized Cost of Energy Analysis November 2018 (New York: Lazard) pp 1–20
[39] Epstein P R et al 2011 Full cost accounting for the life cycle of coal Ann. NY Acad. Sci. 1219 73–98
[40] Esch L and Hendryx M 2011 Chronic cardiovascular disease mortality in mountaintop mining areas of central Appalachian states J. Rural Health 27 350–7
[41] Hendryx M, Ahern M M and Nurkiewicz T R 2007 Hospitalization patterns associated with Appalachian coal mining J. Toxicol. Environ. Health A 70 2064–70
[42] Adgate J L, Goldstein B D and McKenzie L M 2014 Potential public health hazards, exposures and health effects from unconventional natural gas development Environ. Sci. Technol. 48 8307–20
[43] McKenzie L M et al 2018 Ambient nonmethane hydrocarbon levels along Colorado’s Northern front range: acute and chronic health risks Environ. Sci. Technol. 52 4514–25
[44] McKenzie L M et al 2019 Relationship between indicators of cardiovascular disease and intensity of oil and natural gas activity in Northeastern Colorado Environ. Res. 170 56–64
[45] Hansen J and Kharecha P 2018 Cost of Carbon capture: can young people bear the Burden Joule 2 1405–7
[46] Hardisty P E, Sivapalan M and Brooks P 2011 The environmental and economic sustainability of carbon capture and storage JERPH 8 1460–77
[47] Heo J, McCoy S T and Adams P J 2015 Implications of ammonia emissions from post-combustion carbon capture for airborne particulate matter Environ. Sci. Technol. 49 5142–50
[48] Petrescu L, Bonalumi D, Valenti G, Cormos A-M and Cormos C-C 2017 Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage J. Clean. Prod. 157 10–21
[49] Koornneef J, van Keulen T, Faaij A and Turkenburg W 2008 Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2 Int. J. Greenhouse Gas Control 2 448–67
[50] House K Z, Harvey C F, Aziz M J and Schrag D P 2009 The energy penalty of post-combustion CO2 capture & storage and its implications for retrofitting the US installed base Energy Environ. Sci. 2 193–13
[51] Benson S M and Deutch J 2018 Advancing enhanced oil recovery as a sequestration asset Joule 2 1386–9
[52] Arciniegas I M and Hittinger E 2018 Tradeoffs between revenue and emissions in energy storage operation Energy 143 1–11
[53] Hirth L 2013 The market value of variable renewables Energy Econ. 38 218–36
[54] Arvesen A and Hertwich E G 2011 Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment Environ. Res. Lett. 6 045102–10
[55] Martinez E, Sanz F, Pellegrini S, Jiménez E and Blanco J 2009 Life cycle assessment of a multi-megawatt wind turbine Renew. Energy 34 667–73
[56] Meijer A, Huijbregts M A J, Schermer J J and Reijnders L 2003 Life-cycle assessment of photovoltaic modules: comparison of mc-Si, InGaP and InGaP/mc-Si solar modules Prog. Photovolt. Res. Appl. 11 275–87
[57] Sherwani A F, Usmani A and Varun 2010 Life cycle assessment of solar PV based electricity generation systems: a review Renew. Sustain. Energy Rev. 14 540–4
[58] Green F and Denniss R 2018 Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies Clim. Change 150 73–87
[59] Driscoll C T et al 2015 US power plant carbon standards and clean air and health co-benefits Nat. Clim. Change 5 535–40
[60] Bain P G et al 2015 Co-benefits of addressing climate change can motivate action around the world Nat. Clim. Change 6 154–7
[61] Service R F 2016 Cost of carbon capture drops, but does anyone want it? Science 354 1362–3