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The Health Benefits of Clean Energy Policy in the United States

By

Candace Marie Vahlsing

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Health Sciences

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:
Professor John R. Balmes, Chair
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Abstract

The Health Benefits of Clean Energy Policy in the United States

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University of California, Berkeley

Professor John Balmes, Chair

In the past ten years, a drastic shift towards the use of less greenhouse gas intensive fuels for electricity generation has occurred in the United States. At the same time, the U.S. government, states, cities, and businesses began to pursue policies to address climate change. This dissertation advances three research topics. First, this dissertation summarizes how environmental health played a role in advancing U.S. climate policy in the Obama Administration from 2009 – 2016 and identifies additional environmental health literature that could provide evidence to support climate change policy in the future. Second, this dissertation reviews the public health and econometric literature monetizing the health benefits of shifting to lower carbon fuels for electric power generation in the U.S. and identifies the strongest model predictors. Third, this dissertation evaluates whether an innovative exposure metric measuring the shift to lower carbon electricity generation in the U.S. from 2011 - 2012 is directly associated with a change in mortality in the Medicare cohort. The analysis in Chapter 2 found that environmental health literature helped to provide the legal foundation for regulating greenhouse gases through the Clean Air Act and that environmental health literature provided the information necessary to build the economic case for the U.S. Environmental Protection Agency (EPA) to promulgate greenhouse gas standards. Four of the eleven Obama-Biden Administration's major climate change rulemakings would not have been cost-effective without monetizing the health, environmental, and societal benefits. The literature review in Chapter 3 revealed that the range of the monetized benefits of shifting to solar energy is 1-2.7 cents/kWh and 1.3-9 cents/kWh for wind energy in the United States. The analysis in Chapter 4 is the first national epidemiology study examining the direct association between phasing out the generation of traditional high carbon fossil-based electricity and the effect on mortality in the Medicare cohort. Using a difference-in-difference (DID) approach, no statistically significant change in mortality in Medicare enrollees was found when comparing the three intervention groups to the control groups and adjusting for confounding. This dissertation provides further evidence supporting the need to conduct multi-step analyses to determine the health effects of energy policy interventions. The results of this research will be used to advance environmental health science and U.S. energy and climate change policy.

To my parents
Barbara Jean Vahlsing and Fredrick H. Vahlsing, III
for their limitless support.

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Chapter 1. Introduction

This dissertation provides new information to advance climate change and environmental health policy in the United States, including the first national epidemiology study evaluating the direct public health benefit of transitioning to low carbon electricity. The three research topics are:

- **The Importance of Environmental Health in Advancing Climate Change Policy in the Obama Administration and Methods to Improve Durability of Future Climate Change Rulemakings.**

  Chapter 2 argues that one of the most influential tools that allowed the successful promulgation of national climate change standards and policies was environmental health literature. In particular, environmental health literature provided part of the legal, economic, and moral foundation for President Obama to advance U.S. climate change policy. Although empirically, one could assume that the important role of environmental health literature in advancing climate change policy in the United States is indisputable, no peer-reviewed research has summarized its role. This paper summarizes some of the contributions that environmental health literature has made and can continue to make to create more durable climate change policy in the future. The new information elucidates the importance of environmental health literature and direct research in conducting more policy relevant studies that make U.S. climate regulations less vulnerable to shifts in politics.

- **A Literature Review of the Findings and Methodologies Utilized to Evaluate the Monetized Air Quality Benefits of Shifting to Cleaner Electricity Generation Fuels in the United States.**

  Increases in the deployment of renewable energy, more utilization of natural gas, and coal plant retirements are modifying the electricity fuel mix in the United States. Numerous studies have evaluated the monetized health benefits resulting from modifications in electricity production fuels under various spatial and temporal durations, in part or in whole. The majority of methods quantified a portion of this transition – the monetized health benefits from air quality improvements. More recently, authors have built on traditional air quality models to evaluate the health impacts of modifications in energy policy through multi-step models that combine energy dispatch modeling and air quality models. Methods vary from highly technical and data intensive to reduced form. Chapter 3 reviews the current methodologies to measure the monetized health benefits of modifications in electricity fuels in the U.S. across various spatial and temporal parameters, compares their findings, and evaluates the variables that are the strongest predictors within each methodology.

- **Estimating the Impact of Shifting to Low Carbon Electricity on Mortality in the Medicare Population using Energy Indicator Variables.**
  Chapter 4 is the first national epidemiology study to examine the direct association between phasing out the generation of traditional high carbon fossil-based electricity and the effect on mortality. The association between a decrease in megawatt hours (MWh) of high carbon electricity generation fuels in the United States and a change in premature mortality of 341,637 unique Medicare enrollees was tested. The study evaluated a decrease in four indicator variables for MWh of electricity generation from coal power plants in 492 counties from 2011 to 2012, during one of the largest shifts to low carbon electricity fuels in history.

Background

The Role of Environmental Health Literature in Advancing U.S. Climate Change Policy

Since President Barack Obama took office in 2009, the U.S. government, as well as most states, cities, and businesses, have implemented a range of policies to address climate change. The rationale for the promulgation of climate change policy, at least at the Federal level, has often been justified by our collective responsibility to protect the next generation in particular from the health impacts of climate change. Although this rationale provided an impetus to shift to lower carbon electricity, many external factors laid also the groundwork for federal climate change policy, including, among other things, the passage of Assembly Bill 32, a landmark climate change law in California (State of California, 2018), the decreasing cost of renewable energy (U.S. Department of Energy, 2009), and climate change litigation before the U.S. Supreme Court. *Massachusetts v. EPA*, 549 U.S. 497 (2007). However, in order for federal climate change policy to actually take hold, policy-makers needed to marshal a number of analytical tools to justify their positions.

Chapter 2 hypothesizes that one of the most influential tools that allowed the successful promulgation of national climate change standards and policies was environmental health literature. In particular, that environmental health literature provided the legal, economic, and moral foundation for President Obama to advance U.S. climate change policy in an adversarial political climate. Although, empirically, one could assume that the important role of environmental health literature in advancing climate change policy in the United States is indisputable, no peer-reviewed research has evaluated its role.

The Strongest Predictor Variables of Monetized Health Benefits of Low Carbon Electricity

Increases in the deployment of renewable energy, more utilization of natural gas, and coal plant retirements are modifying the electricity fuel mix in the United States. Numerous studies have evaluated the monetized health benefits resulting from modifications in electricity production fuels under various spatial and temporal durations, in part or in whole. Research has focused on the health benefits of climate mitigation policies (Bell, 2008; Markandya, 2009; Nemet, 2010; Haines, 2009; Smith, 2008; Vennemo, 2006; Markandya, 2009; Burtraw, 2003; Cifuentes, 2001; Haines, 2006; Haines 2012; Wilkinson, 2009). Some of these authors also indirectly consider the benefits of increasing renewable energy generation and improving energy efficiency. The majority of methods quantify a portion of this transition by monetizing health benefits from air quality improvements. More recently, authors have built on traditional air quality models through adding energy dispatch modeling and exposure modeling to evaluate the health impacts of modifications in energy policy. Methods vary from highly technical and data intensive to reduced form.

The current literature on the health benefits of shifting to low carbon electricity generally falls within three categories: models that estimate the monetized health benefits of modifications in air quality (Pope, 2002; Laden, 2006; Fann, 2012; Fann, 2009; Buonocore, 2014; Penn, 2017), models that quantify the impact of modifications in electricity generation on air quality (Valentino, 2012; Cullen, 2013; Kaffine, 2013; Buonocore, 2016), and models that connect the first two types of models to estimate the monetized benefit of modifications in electricity fuel policy (McCubbin, 2011; Siler-Evans, 2013; Millstein, 2017; U.S. Department of Energy, 2015; Wiser, 2016; Buonocore, 2016; Machol, 2013; Kerl, 2015; National Research Council, 2010; U.S. EPA, 2015; Severnini, 2017). Chapter 3 focuses on reviewing the literature regarding the third category of models. In particular, Chapter 3 reviews the current econometric methodologies to measure the monetized health benefits of shifting to low carbon electricity in the U.S. across various spatial and temporal parameters. The goal of the review is to ascertain the model parameters that are the strongest predictors of the outcome -- in this case the monetized health benefit per kilowatt hour (kWh) -- of various electricity fuels. A brief review of the results of models in the first two categories is also provided.

The Association between Low Carbon Electricity Fuels and Premature Mortality in the United States

Substantial literature is available estimating the health benefits of the transition to low carbon electricity using energy and economic dispatch modeling and analyses of the national and global burden of disease attributed to air pollution from power plants, (Health Effects Institute; 2016). However, to date, there are no national epidemiology studies that measure the direct association between shifting to low carbon energy generation and health outcomes, where the exposure metric is megawatt hours (MWh) of various electricity fuels. Rather, publications that have used methods closest to directly measuring exposure using electricity generation in epidemiology studies have used proximity to the power plant as an indicator of exposure. Recently, Casey et al. found an increase in fertility rates and a decrease in preterm births in California mothers following the retirement of coal-fired power plants within 10 kilometers of their residence in California (Casey, 2018a; Casey, 2018b). But these publications do not account for the proportion of changes in the health outcome attributed to shifting to low carbon electricity fuels. This research, in Chapter 4, builds on the vast epidemiology literature on air pollution and health and measures the direct association of low carbon electricity generation to premature mortality in the Medicare population.

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Collectively, several components of this dissertation are innovative. This research is the first to document the role that environmental health played in the advancement of climate change policy in the Obama Administration and to identify new environmental health literature needed to create more durable environmental regulations that are able to survive Administrations of different political parties through providing strong scientific, economic, and legal footing. This dissertation also contains the first literature review of models and methods to monetize the health benefits of shifting to low carbon fuels for electricity generation in the U.S. and that identifies the strongest model predictors. A better understanding of the model predictors in econometric analyses of the health benefits of modifications in electricity fuels will inform new econometric models and epidemiology studies. Lastly, this dissertation includes the first national epidemiology study to evaluate the direct association between a decrease in MWh of high carbon electricity fuels from 2011-2012 and mortality in the Medicare cohort. The research findings will be valuable for validating the numerous econometric models estimating the health benefits of electricity policies and to inform energy policy decisions.

Chapter 2. The importance of environmental health in advancing climate change policy in the Obama Administration and methods to improve durability of future climate change rulemakings.

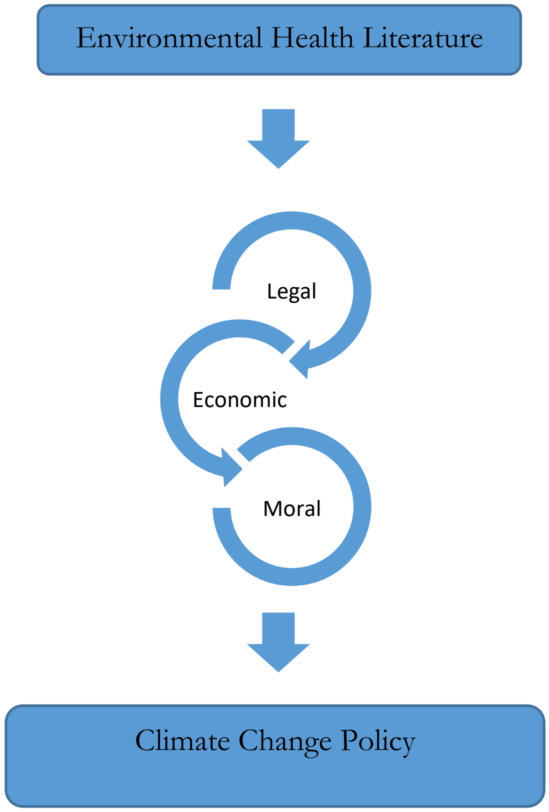
When President Barack Obama took office in 2009, the rationale for the promulgation of climate change policy, at least at the federal level, was often justified by our collective responsibility to protect the next generation, in particular from the health impacts of climate change. Many factors laid the groundwork for federal climate change policy, in particular, the passage of Assembly Bill 32, a landmark climate change law in California (California Global Warming Solutions Act of 2006) the decreasing cost of renewable energy (U.S. DOE; 2009) , and litigation (*Massachusetts v. EPA*, 549 U.S. 497 (2007).

Figure 1. Drivers Advancing Federal Climate Change Policy in the Obama Administration

Political	Moral	Economic	Legal	Scientific
Federal: 1992 Congress Approves UNFCCC State: CA AB 32	Messaging: Obama CAP Speech; Pope encyclical Polling: 2016 shift to recognizing U.S. health impacts	Decreasing price of renewable energy technologies Increase in private investment in renewable energy	1999 Lawsuit against EPA to promulgate GHG standards 2007 Mass v. EPA	Increasing EHS literature on the **current** and future health impacts of climate change in the U.S.

This paper argues that one of most influential tools that allowed the successful promulgation of national climate change standards and policies was environmental health literature. In particular, the environmental health literature provided the legal, economic, and moral foundation for President Obama to advance U.S. climate change policy. Although, conceptually, one could assume that environmental health literature played an important role in advancing climate change policy in the United States, no peer-reviewed research has summarized its role.

Figure 2. Framework for Understanding the Role of EHS Literature in Advancing Climate Change Policy



Although the Trump Administration is attempting to dismantle the climate change regulatory infrastructure promulgated under President Obama, in part, by discrediting science, there are actions that can be taken to preserve these policies. This paper summarizes some of the contributions that environmental health literature has made and can continue to make to create more durable and efficient climate change policy in the future. It is important to understand the role that environmental health literature has played in creating climate policy and regulations in order to identify research and data gaps, to identify areas to invest new research, and to document the evidence base used to inform policy development. The new information in this paper elucidates the importance of environmental health literature and direct research in conducting more policy relevant studies that make U.S. climate regulations less vulnerable to shifts in politics.

Methods

Obama Administration policy and communications documents were analyzed to assess the role of environmental health literature in providing the 1) legal, 2) economic, and 3) moral justification to advance climate change policy.

Three types of research were conducted. Legal databases were searched to determine the role that environmental health literature played in the historic Supreme Court decision *Massachusetts v.*

U.S. Environmental Protection Agency (EPA) which required EPA to evaluate whether greenhouse gas emissions "endangered" public health and welfare under the Clean Air Act, called the "endangerment finding, which EPA later published in 2009. In particular, the litigation on climate change that helped build the case for *Massachusetts v. EPA* and the subsequent endangerment finding was identified and reviewed to determine if EPA cited environmental health literature in making the case.

The highest cost U.S. climate change regulations published in the Obama Administration were evaluated to determine the role of environmental health literature in providing the economic justification to promulgate climate change regulations, *i.e.*, to determine whether health impacts were considered in the rule making and in what level of detail, and to determine the additional research needed to draft climate change regulations in the future. The regulations were identified by searching climate regulations that went to OMB for review. For example, regulations were reviewed to determine which climate change regulations described the health benefits qualitatively and which quantified the public health benefits, including the social cost of carbon and methane, based on environmental health literature.

Communications literature, including speeches and remarks, press releases, social media, and policy documents were reviewed to determine the role that environmental health findings played in providing the moral justification to address climate change and to advance non-regulatory climate policy.

Figure 2. Summary of Methods

Environmental Health Literature Provided the Legal Foundation for Regulating Greenhouse Gases through the Clean Air Act

From 1998 to 2007, the EPA waivered in its determination of whether the agency had the legal authority to directly regulate greenhouse gas emissions through the Clean Air Act. In 2007, the Supreme Court directed EPA to formally evaluate if carbon pollution adversely impacted public health and welfare. This process codified the importance of environmental health literature in advancing climate change policy in the United States, in particular, the importance of providing the evidence to legally regulate carbon pollution through the Clean Air Act.

The Clean Air Act[1] requires an air pollutant to adversely impact public health or public welfare in order for EPA to have the legal authority to develop a regulation minimizing the emissions of that air pollutant. Under President William J. Clinton, in 1998 EPA determined that it had the legal authority to regulate greenhouse gases through the Clean Air Act. EPA, however, it did not utilize that authority. In 1999, to spur EPA into action, environmental organizations and renewable energy industry organizations filed a petition requesting EPA regulate greenhouse gas emissions under the Clean Air Act, in particular greenhouse gases from vehicles, the largest source of emissions at the time. When considering the petition in 2003, the George W. Bush Administration's EPA found that despite the Clinton EPA's previous determination, it did not have the authority to regulate greenhouse gases under the Clean Air Act and denied the petition. *Massachusetts v. EPA*, 549 U.S. 497 (2007). The petitioners took the case through the litigation system to the Supreme Court through the case, *Massachusetts v. EPA.*

Evidence Used to Make the Case that Greenhouse Gases should be Regulated

Part of the petitioner's brief for *Massachusetts v. EPA* was underpinned by EPA's failure to properly consider the science and determine if greenhouse gas emissions from vehicles endanger public health and welfare. They wrote in their brief before the Court, "Mere incantation of the words 'scientific uncertainty,' paired with terse and selective references to the state of the science, is not a substitute for the mature scientific inquiry plainly contemplated by section 202(a)(1) of the Clean Air Act. Whether air pollutants associated with climate change may be reasonably anticipated to endanger public health or welfare 'is a matter for the agency to decide, but it must bring its expertise to bear on the question." *Massachusetts v. EPA*, 2006 U.S. S. Ct. Briefs LEXIS 790.

In *Massachusetts v. EPA,* the Supreme Court considered "the statutory question" of "whether sufficient information exists [for EPA] to make an endangerment finding." *Massachusetts v. EPA*, 549 U.S. 497, 534-35 (2007). The Court held that "EPA ha[d] offered no reasoned explanation for its refusal to decide whether greenhouse gases cause or contribute to climate

[1] Sections that require impacts before regulations.

change" and directed EPA to "ground its reasons for action or inaction" in the Clean Air Act. In practice, this meant that EPA had to determine if greenhouse gases endangered public health and welfare, i.e., make an "Endangerment Finding".

The Court's decision regarding the need for "sufficient information" created the framework which would later result in environmental health literature providing the legal foundation to support regulating greenhouse gases. In response to the decision, the EPA reviewed the published literature on the impact of greenhouse gas emissions on public health. In 2007, the George W. Bush Administration finalized a draft of the Endangerment Finding, however, the White House did not release the document to the public for unknown reasons (Morford, 2009).

Evidence Used to Establish Greenhouse Gases Harm Public Health in the Endangerment Finding

President Obama began his climate legacy by unlocking the opportunity to directly regulate greenhouse gases under the Clean Air Act (as envisioned in *Massachusetts v. EPA*) by directing the EPA to make a new Endangerment Finding.

On December 7, 2009, the EPA under President Obama, released a new Endangerment Finding, which determined that *elevated concentrations of the six greenhouse gases in the atmosphere—carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6)—endanger both the public health and the public welfare of current and future generations* (U.S. EPA, 2009). The public health impacts documented in the final endangerment finding conducted under Section 202(a) of the Clean Air Act, clarified the perceived ambiguity and provided the legal authority for EPA to develop regulations for greenhouse gases for the first time in history (42 U.S.C. 85, II, A §7521).

Environmental health literature on the public health impacts of climate change in the U.S. provided the scientific evidence EPA needed to make their determination. EPA's Endangerment Finding[2] was underpinned by hundreds of environmental health publications aggregated mainly through the U.S. Climate Change Science Program (U.S. CCSP (2008b)), previous EPA publications, and the human health and North America chapter of the Intergovernmental Panel on Climate Change (IPCC) Working Group II Assessment Report (Field, 2007; Confalonieri, 2007). The final Endangerment Finding provided evidence that greenhouse gas emissions

[2] U.S. EPA, "Technical Support Document for Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act." *Climate Change Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency*, 7 Dec. 2009, https://www.epa.gov/sites/production/files/2016-08/documents/endangerment_tsd.pdf. Accessed 11 August 2020.

adversely impact public health through the following mechanisms that were supported by environmental health literature:

- Increase in health effects from rise in ambient ozone (Denman, 2007; Jacob and Winner, 2009; Mickley, 2004; Hogrefe, 2004; CCSP, 2008b; Field, 2007; Confalonieri, 2007)
- Increase in mortality and morbidity from a rise in average temperatures, and therefore the probability of heatwaves (Confalonieri, 2007; Ebi, 2008; Karl, 2009)
- Increase in adverse effects from extreme weather events, in particular hurricanes and floods (Confalonieri, 2007; Ebi, 2008)
- Adverse impacts from sea level rise and the resulting increase in coastal storms (Nicholls, 2007; CCSP, 2009b)
- With a lower strength in weight of the evidence, changes in aeroallergens and the associated increase in allergic illnesses (Ebi, 2008) and increases in vector-borne diseases (U.S. EPA, 2009; Field, 2007; Karl, 2009; Peterson, 2008; CCSP, 2008b)

EPA also found that certain populations are more vulnerable to the health impacts of climate change, including children, the poor, people with preexisting illness, and the elderly (Ebi, 2008; Graumann, 2005; Nicholls, 2007).

EPA's determination laid the groundwork for the promulgation of greenhouse emission standards for the highest polluting source categories, including: vehicles and trucks in 2010, 2012, and 2016 (30 percent of greenhouse gas emissions); power plants (30 percent of greenhouse gas emissions) in 2014 and 2015; oil and gas production facilities (10 percent of greenhouse gas emissions) in 2016; and additional permitting requirements for large stationary sources and more.

It is worth noting that the environmental health data that underpinned the endangerment finding included both U.S. and global data. Most of the data cited in the endangerment finding was from the U.S. Climate Change Science Program. EPA also relied on environmental and health monitoring data from the National Oceanic and Atmospheric Administration (NOAA), the Centers for Disease Prevention and Control (CDC), and many additional agencies. While collaboration should be promoted to streamline methods and funding, history has shown that global consensus on a scientific finding is not always sufficient to motivate U.S. policy initiatives. For example, the Trump Administration excluded studies on the global impacts of climate change from the revision of the social cost of carbon. Therefore, in order to create durable policy, is it imperative to continue to promote new environmental health literature and monitoring data on the health impacts of climate change in the United States. The U.S. government should continue to prioritize funding for these programs.

Environmental Health Literature Provided the Information Necessary to Build the Economic Case for EPA to Promulgate Greenhouse Gas Standards

This paper argues that environmental health literature, mainly environmental epidemiology, provided the evidence to bolster the economic case necessary for the Obama Administration to promulgate economically justifiable greenhouse gas rules.

With the exception of the National Ambient Air Quality Standards (NAAQS) promulgated by EPA, federal agencies are not limited in considering cost-effectiveness when developing and finalizing a climate change regulation. *Whitman v. American Trucking Assns*., Inc., 531 U.S. 457 (2001). The White House's Office of Management and Budget's Office of Information and Regulatory Affairs (OIRA) requires regulations that are sent to the White House for review to be net beneficial from a cost perspective. President Reagan established this requirement in Executive Order (EO) 12291, which stated that regulatory alternatives must maximize the net benefits to society, in particular, the alternative with the least net cost to society should be chosen (Executive order 12291, 1981). The EO was amended slightly by several Presidents, however, it has largely remained intact. More recently, the Trump Administration reinforced the EO, stating that new regulations should be net beneficial to the public (Rao, 2017).

Regulations determined to have an annual economic impact of $100 million or more are considered "major" rulemakings and required to submit a Regulatory Impact Analysis (RIA) to OIRA quantifying the cost and benefits of each alternative considered in the rulemaking, including the net economic benefits of the regulation (U.S. Office of Management and Budget, 2016). In effect, this requirement means that when OIRA reviews a new or revised regulation to determine whether the agency should modify the standard before it is issued, OIRA hones in on the net economic benefit of the regulation quantified in the RIA. In plain terms, in line with the direction from EO 12291, if at least one of the regulatory alternatives in an environmental rulemaking does not result in net economic benefits to society, that regulation is often sent back to the promulgating agency for revision or not published, the exception being the NAAQS.

Due to the requirement to promulgate net beneficial regulations, substantial effort is directed towards the methodology used to quantify the costs and benefits of rulemakings. In EPA's criteria air pollution regulations, avoided premature mortality from particulate matter 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) and respiratory health conditions resulting from exposure to ground level ozone often are responsible for the largest monetized benefits of a rulemaking. The health benefits from air quality improvement also play a strong role in some greenhouse gas standards.

Another metric, initially called the social cost of carbon (SC-CO2), which environmental health literature contributed to the development of, is also utilized to monetize the value of reducing greenhouse gas emissions in rulemakings (Interagency Working Group on Social Cost of Carbon, United States Government; 2010). According to EPA, "[t]he SC-CO2 is meant to be a comprehensive estimate of climate change damages and includes, among other things, changes in net agricultural productivity, human health, property damages from increased flood risk and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning." (U.S. EPA, 2016). The SC-CO2 was initially developed in 2010 and revised in 2013 and again in 2016, to fine tune the estimate based on recommendations from the National Academies of Sciences, Engineering, and Medicine (National Academies of Sciences, Engineering, and Medicine, 2016). In 2016, the social costs of methane (SC-CH4) and nitrous oxide (SC-N2O) were established (U.S. Council of Economic Advisers, 2016).

Figure 3 summarizes the role that the monetized direct benefits of air quality (AQ) improvements and monetized health, environmental, and societal benefits through the social cost of carbon played in the 11 largest major climate change regulations promulgated in the Obama Administration. Nine out of 11 of the regulations are EPA rulemakings, one is from the Department of Interior's Bureau of Land Management (BLM), and one is from the U.S. Department of Energy (DOE). All 11 of the regulations cited environmental health literature in their Regulatory Impact Assessment and quantify the social cost of carbon or methane. Eight of the regulations quantified the *direct* health benefits of air quality improvements. The three remaining regulations that did not quantify the direct health benefits were all rulemakings to reduce methane emissions. In two of the rulemakings, one for oil and gas production and another for landfills, EPA provided a qualitative summary of the health benefits. In the remaining BLM rulemaking for methane waste, the health benefits from air quality improvements were not included in the RIA. Nearly all of the rulemakings noted limitations to their AQ health benefits analyses due to insufficient data, whether quantitative or qualitative.

An evaluation of how the monetized health and social benefits contributed to making major climate change rulemakings in the Obama Administration found the following results. Four of the eleven rulemakings would not have been cost-effective without monetizing the health, environmental, and societal benefits. The six rulemakings that remained cost-effective were due to savings in fuel or energy security (EPA rules for cars and trucks and EPA Renewable Fuel Standard) or energy savings (DOE energy conservation standards).

Figure 3. Review of Role of Health Benefits Assessment in Major Climate Standards Promulgated in the Obama Administration[3]

Major Regulation	Agency	AQ and SC Health Benefits Quantified in RIA	Regulation Cite EHS Literature?	Health Benefits Quantified If yes, any limitations? If No, rationale?	Rule Cost-Effective without AQ and SC Health Benefits
Standards of Performance for Greenhouse Gas Emissions From New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units	EPA	AQ - Yes SC - Yes	Yes	"The EPA's finding of no new non-compliant units (and therefore, no projected costs or quantified benefits) is robust . . . Benefits and costs presented in the illustrative analyses."	N/A[4]
Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	EPA	AQ - Yes SC - Yes	Yes	"These models assume that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality because the scientific evidence is not yet sufficient to allow differentiation of effect estimates by particle type"	No
Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources	EPA	AQ - No, health effects qualitatively discussed. SC – Yes.	Yes	"While we expect that the avoided emissions will result in improvements in ambient air quality and reductions in negative health effects associated with exposure to HAP, ozone, and particulate matter (PM), we have determined that quantification of those benefits cannot be accomplished for this rule.5 This is not to imply that there are no health benefits anticipated from the final NSPS; rather, it is a reflection of the difficulties in modeling the direct and indirect impacts of the reductions in emissions for this industrial sector with the data currently available." "[Q]uantification of the VOC-related health benefits cannot be accomplished for this rule in a defensible way." "Due to data limitations regarding potential locations of new and modified sources affected by this rulemaking, we did not perform the air quality modeling needed to quantify PM2.5 benefits associated with reducing VOC emissions for this rule." "Due to data limitations regarding potential locations of new and modified sources affected by this rulemaking, we did not perform air quality modeling for this rule needed to quantify the ozone benefits associated with reducing VOC emissions."	No
Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule (2011)	EPA DOT	AQ - Yes SC - Yes	Yes	"[T]he full complement of human health and welfare effects associated with PM and ozone remain unquantified because of current limitations in methods or available data. We have not quantified a	Yes, due to fuel savings.

[3] AQ (Air Quality), SC (social cost of greenhouse gas emissions), DOT (Department of Transportation), DOE (Department of Energy), DOI (Department of Interior), BLM (DOI's Bureau of Land Management), VOC (volatile organic compound).

[4] EPA determined that the rule was not expected to have a cost. However since the rule signified a major policy change, an RIA was conducted. https://www3.epa.gov/ttnecas1/docs/ria/utilities_ria_final-nsps-egus_2015-08.pdf

				number of known or suspected health effects linked with ozone and PM for which appropriate health impact functions are not available or which do not provide easily interpretable outcomes (e.g., changes in heart rate variability)."	
Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2 (2016)	EPA DOT	AQ - Yes SC - Yes	Yes	"There are several health benefit categories that EPA was unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. Because the NOX and VOC emission reductions associated with the final program are also precursors to ozone, reductions in NOX and VOC would also reduce ozone formation and the health effects associated with ozone exposure. Unfortunately, ozone-related benefits-per-ton estimates do not exist due to issues associated with the complexity of the atmospheric air chemistry and nonlinearities associated with ozone formation."	Yes, due to fuel savings.
Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule (2010)	EPA DOT	AQ - Yes SC - Yes	Yes	"We have not quantified a number of known or suspected health effects linked with ozone and PM for which appropriate health impact functions are not available or which do not provide easily interpretable outcomes (e.g., changes in heart rate variability)."	Yes, due to fuel savings.
2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards (2012)	EPA DOT	AQ - Yes SC – Yes	Yes	"However, the full complement of human health and welfare effects associated with PM, ozone, and other criteria pollutants remain unquantified because of current limitations in methods or available data. We have not quantified a number of known or suspected health effects linked with ozone, PM, and other criteria pollutants for which appropriate health impact functions are not available or which do not provide easily interpretable outcomes (e.g., changes in heart rate variability)."	Yes, due to fuel savings.
Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills	EPA	AQ - No, health effects qualitatively discussed. SC - Yes	Yes	"[D]etermined that quantification of those benefits cannot be accomplished for this rule in a defensible way. This is not to imply that these benefits do not exist; rather, it is a reflection of the difficulties in modeling the direct and indirect impacts of the reductions in emissions for this industrial sector with the data currently available."	No
Waste Prevention, Production Subject to Royalties, and Resource Conservation	BLM, DOI	AQ - No, no qualitative discussion of health effects. SC - Yes	Yes	"Although the analysis monetizes the benefits of reduced methane releases and the costs of carbon dioxide additions, the analysis does not monetize the benefits to public health and the environment of reducing VOC emissions by 250,000 – 267,000 tons per year and reducing emissions of hazardous air pollutants."	No, except for upper bound of fuel savings from liquids unloading.
Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air Conditioning and Heating Equipment and Commercial Warm Air Furnaces	DOE	AQ - Yes SC - Yes	Yes	Estimate health benefits of NOx emissions, not SO_2 emissions. "DOE estimated the monetized value of NOX emissions reductions using benefit per ton estimates from the Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants and Emission Standards for	Yes, due to energy savings.

				Modified and Reconstructed Power Plants, published in June 2014 by EPA's Office of Air Quality Planning and Standards."	
Renewable Fuel Standard (RFS2): Final Rule Additional Resources	EPA	AQ - Yes SC - Yes	Yes	"The final emission inventories do not include vehicle-related PM reductions associated with E85 use . . . Most significantly, our modeling of the air quality impacts of RFS2 relied upon interim inventories that assumed that ethanol will make up 34 of the 36 billion gallon renewable fuel mandate, that approximately 20 billion gallons of this ethanol will be in the form of E85, and that the use of E85 results in fewer emissions of direct PM2.5 from vehicles. The emission impacts, air quality results and benefits analysis would be different if, instead of E85, more non-ethanol biofuels are used or mid-level ethanol blends are approved and utilized."	Yes, due to energy security. AQ resulted in net costs.

Figure 4 summarizes the percent of the monetized benefits of each rulemaking that is due to the direct health impacts from air quality improvements and health, environmental, and societal benefits (called health-related benefits). The percentage was calculated by dividing the total monetized health benefit of the rulemaking, found in each RIA, by the total economic and health benefits of the rulemaking. When the RIA includes a range of monetized health benefits a range is also presented in Figure 4. Additional information on the scenario evaluated in the footnote in Figure 4.

The analysis found that 9-100 percent of the benefits in major climate change rulemakings promulgated in the Obama Administration were due to health-related benefits, with one exception for the Renewable Fuel Standard (RFS). In three of the climate change rulemakings, 100 percent of the monetized benefits are health-related. Those include regulations for the electricity sector, oil and gas sector, and landfills. Health-related benefits compromised the smallest proportion of the monetized benefits in EPA's rulemakings for cars and trucks, ranging from 9-34 percent. In DOE's appliance standards for air conditioners and furnaces, health-related benefits were responsible for 31 percent of the monetized benefits.[5]

EPA's RFS regulation was the only standard analyzed that, under certain scenarios, resulted in an increase in ozone and $PM_{2.5}$ and related premature mortality (33 - 165 additional cases in 2022 (U.S. EPA, 2010)). EPA determined that $PM_{2.5}$, NOx, and subsequently ozone is likely to increase due to processing at renewable fuel plants and fuel transportation (U.S. EPA, 2010). The adverse air quality impacts of the RFS standard were subsumed by the SC benefits that were 10 times the cost of the air quality impacts. If the RFS is revised after the statutorily mandated fuel

[5] The health-related benefits were calculated by dividing the sum of the AQ and SC benefits by the total benefits of the rulemaking.

limits expire in 2022 or if there is an interest in adopting an approach similar to California's Low Carbon Fuel Standard (LCFS), consideration should be given to designing a program to minimize air quality impacts.

This paper is the first evaluation of the role that direct air quality impacts and social cost of carbon play in determining the net-benefits of major climate change regulations. The analysis demonstrates the important role that health-related benefits, and therefore environmental health literature, played in the economic justification of major climate change rulemakings in the Obama Administration. The finding that 9-100 percent of the benefits in major climate change rulemakings promulgated in the Obama Administration were due to health-related benefits, with one exception for the Renewable Fuel Standard, proves this claim. In addition, four of the rulemakings evaluated would not have been cost-effective if the health-related benefits were excluded from the regulatory impact analysis and the standards would have been difficult to promulgate.

All of the major climate regulations cited epidemiology studies that quantified the association between the expected change in air quality and morbidity or mortality, which were then used to determine the monetized health benefit of the standards. There is a serious lack of air quality modeling and epidemiology studies evaluating the health benefits of reducing methane emission from oil and gas production and solid waste systems. For this reason, EPA RIA's have not quantified the local health benefits of reducing methane emissions. This deficiency is counterbalanced by the social cost of methane in the cost-benefit analysis, however, additional environmental health literature on the direct air quality benefits would result in more informed regulations.

Figure 4. Percent of Major Climate Change Regulations Benefits from AQ and SC

Major Regulation	Percent of Benefits from AQ and SC
Standards of Performance for Greenhouse Gas Emissions From New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units	N/A
Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	100
Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources	100
Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule (2011) [6]	15
Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2 (2016) [7]	34
Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule (2010) [8]	9-11
2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards (2012) [9]	18
Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills	100
Waste Prevention, Production Subject to Royalties, and Resource Conservation	61-90
Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air Conditioning and Heating Equipment and Commercial Warm Air Furnaces[10]	31
Renewable Fuel Standard (RFS2): Final Rule Additional Resources	0-38

A more detailed analysis indicates the direct AQ health benefits of EPA's Clean Power Plan vastly outweigh the costs. EPA's Clean Power Plan would cost up to $8.4 billion when fully implemented. This is balanced with up to $34 billion to $54 billion of total benefits, of which up to 41 to 63 percent ($14 billion - $34 billion) when the rule was to have been fully implemented in 2030 are attributed to health benefits from avoided air pollution emissions[11] and $20 billion in benefits from avoided climate change impacts. The highest proportion of the monetary value of avoided health impacts was attributed to avoid premature mortality.[12] The net benefits of the Clean Power Plan when fully implemented would have been $26 billion – $45 billion.

The importance of quantifying the value of health benefits in order to justify the cost benefits of the Clean Power Plan is more pronounced when evaluating the early years of the program. In 2020, climate change benefits only result in $2.8 billion, while the cost of the rulemaking is $2.5

[6] At 3% SC discount, annualized value.
[7] At 3% SC discount, annualized value.
[8] At 3% SC discount. Low case is 2020, high case is 2050.
[9] At 3% SC discount.
[10] At 3% SC discount.
[11] 2030 benefits estimates for rate-based compliance using 3 percent discount. Using Lepeule, 2012 and Levy, 2005 for premature mortality estimates. https://www3.epa.gov/ttnecas1/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf. More conservative estimates of the health benefits yield a slightly lower weight on health, in this scenario 41 percent of the Clean Power Plan's benefits are due to avoided health outcomes.
[12] According to CPP RIA, 98 percent of the monetary benefits of air pollution are due to avoided premature mortality.

billion, bringing the net benefits of the Clean Power Plan in 2020 to $300 million. Increasing the climate benefits with $700 million – 1.8 billion in additional health benefits brings the net benefit of the rule to $1 – 2.1 billion, making the justification for the rulemaking much more compelling.

The strong contribution of health benefits to the economic justification of the Clean Power Plan rulemaking did not go unnoticed by the Trump Administration, in particular, that 90 – 98 percent of the health benefits of the standard are due to avoided premature mortality and the social cost of carbon.

The Trump Administration's revision of the Clean Power Plan includes two main alternative methods to calculate the avoided premature mortality from $PM_{2.5}$ and ozone through NO_x and SO_2 reductions due to the regulation.

First, EPA calculates avoided premature mortality above the lowest measured level (LML) of $PM_{2.5}$ exposure instead of the entire exposure profile in two environmental health epidemiology studies used to evaluate premature mortality avoided (Krewski, 2009; Lepuele, 2012). Through this method, EPA is creating a threshold below which it does not include the benefits. EPA justifies this as appropriate since there is less certainty around the impact of exposure at lower concentrations.

EPA employs another modification that reduces the health benefits of the rulemaking. EPA only quantifies the avoided premature mortality that will result from reductions in exposure to $PM_{2.5}$ from the Clean Power Plan in locations where air pollution is above the NAAQS of 12 ug/m3. The imposition of a threshold for premature mortality at 12 ug/m3 is not justifiable based on the published literature (Frey, 2020). A number of researchers have cautioned against establishing a threshold under which $PM_{2.5}$ has no effects. In the $PM_{2.5}$ NAAQS Integrated Science Assessment that justified the NAAQS, EPA concluded that there is little evidence to show there is a $PM_{2.5}$ threshold under which there are no impacts, (U.S. EPA, 2009b). EPA reiterates this finding in the revised Clean Power Plan, yet, uses their modified approach (U.S. EPA, 2019). The World Health Organization has also cautioned against underestimating the health implications of low exposure to $PM_{2.5}$. In fact, the World Health Organization's Air Quality Guideline (ACG) for $PM_{2.5}$ is 10 ug/m3, below the $12_{ug/m3}$ threshold EPA picked (World Health Organization, 2016).

In 2008, three years after the AQG was established, many countries had standards more stringent than the AQG. Therefore it is likely that the current EPA administration is undervaluing the benefit of $PM_{2.5}$ and correlated avoided premature mortality through only quantifying the benefits above 12 ug/m3 (Vahlsing, 2012).

The combined effect of these two changes to the health benefit quantification methodology, in addition to the changes in the policy of the rulemaking, has led the revised version of the rule to result in 6 percent of the direct health benefits of the Obama Administration rulemaking.

The Trump Administration also revised the social cost of carbon to weaken it substantially through a variety of means that have resulted in a value that, according to the Government Accountability Office is seven times lower than the Obama Administration metric (U.S. Government Accountability Office, 2020).

The EPA and NHTSA MY2012 – MY2016 fuel economy and greenhouse gas standards for cars resulted in health benefits at $1.2 billion to $1.3 billion when fully implemented (U.S. EPA, 2010) due to reductions in $PM_{2.5}$ and ozone emissions. Although the health benefits of the fuel economy rulemaking were not substantial when compared to the total benefits of the rulemaking, which largely resulted from fuel savings, the health benefits are still important when comparing cost benefits to the cost of the rulemaking.

The environmental health literature had a strong influence in determining the cost benefits and therefore the economic feasibility of promulgating major climate change regulations. It has such a large impact on the economic benefits that the Trump Administration is adopting alternative methods to minimize the weight of the health benefits.

Although the economic benefits from environmental health literature were quantified for most of the regulations, they were incomplete. Figure 3 above summarizes some of the rationale provided by the agencies of the limitations in their analyses. The Regulatory Impact Assessments (RIAs) failed to quantify the health benefits of avoided mercury, NOx, and hazardous air pollutant (HAP) emissions. This is not unique. Many climate change regulations promulgated during the Obama Administration did not quantify any of the health benefits from air quality improvements due to a lack of environmental health literature, monitoring. and industry information. Additional examples of these regulations and the opportunities for additional environmental health literature to inform climate change regulations in future Administrations are provided in the discussion.

Public Health Helped Provide the Political Justification for the President to Promulgate Greenhouse Gas Policy Reframe

This paper argues that public health literature helped provide the moral rationale and the political justification for addressing climate change during the Obama Administration. In particular, that environmental health literature on the public health impacts of climate change helped provide the opportunity for President Obama to make public health a core message in his campaign to address climate change.

Although many Americans understood that increasing greenhouse gas emissions would result in changes to the Earth's climate in the future, when President Obama took office, it was not common knowledge that climate change was impacting the current generation of American children. Despite the fact that multiple published environmental health studies provided evidence that climate change is already impacting Americans and polling indicating the doctors noticed the impacts in their patients (*RT Magazine*, 2015), common understanding and political rhetoric had not caught up with reality. Only 50 percent of Democrats and 29 percent of Republicans perceived that climate change will pose a serious threat in their lifetime (Dunlap, 2008).

In order to shift national thinking, President Obama began emphasizing the impacts of climate change on the current generation. Environmental health literature had indicated that warmer temperature was resulting in higher levels of ozone and, in turn, asthma attacks in children (The White House, 2014). To simplify this message, the President would often articulate that it was the nation's responsibility to address climate change in order to prevent more children from getting asthma attacks. In addition, to easily communicate the connection between climate change and health, President Obama and his Cabinet frequently utilized the term carbon pollution (Google Trends (a), 2020). This term portrayed the connection between the health impact of criteria air pollution and greenhouse gases. Google Trends indicates that although the term has a long history, its peak utilization was in August, 2014 during the publication of the draft Clean Power Plan (Google Trends (b), 2020).

The increase in President Obama's public health messaging around climate change during the course of his presidency is illustrated through his public remarks. President Obama frequently spoke of the moral imperative to address climate change. While his rationale to address climate change began to "protect the one planet we got for future generations" it expanded to include a more present day rationale "to protect the health of our children". In particular, although framing climate change as a public health issue began during his first campaign, it became increasingly more punctuated when discussing protecting the health of future generations during his second term (Obama, B., 2007; 2008; 2013).

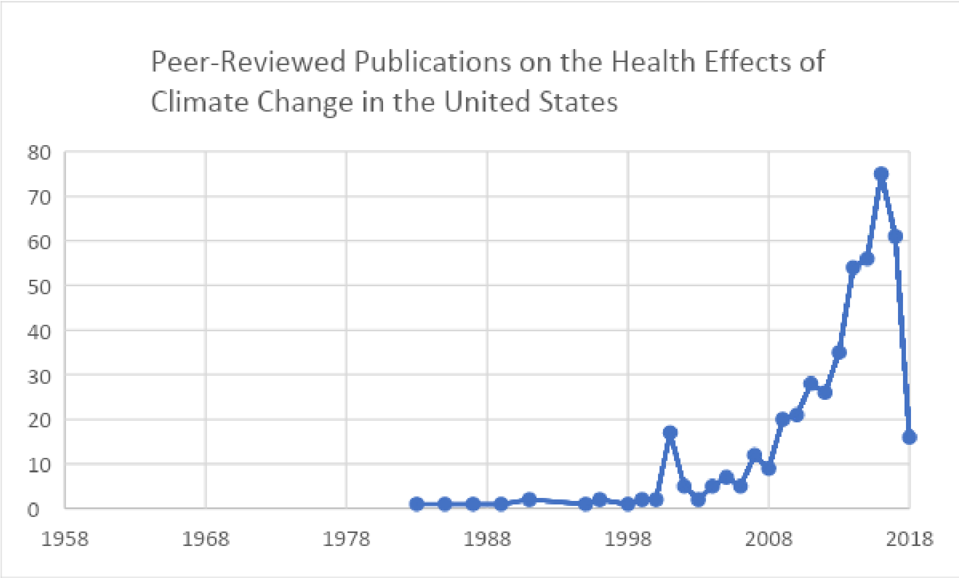
- During his first campaign for the Presidency, Senator Obama pronounced *This is not the future I want for my daughters. It's not the future any of us want for our children.*
- When providing the justification for the Climate Action Plan on June 25, 2013, President Obama spoke of the need to reduce the health impacts of climate change, *So today, for the sake of our children, and the health and safety of all Americans, I'm directing the Environmental Protection Agency to put an end to the limitless dumping of carbon pollution from our power plants, and complete new pollution standards for both new and existing power plants.*

President Obama's remarks around the launch of the Climate Action Plan was one of the first times he made the direct link between the need to address climate change to improve the health of Americans in a formal address. From this point on, one would be hard pressed to find a speech where he did not provide reducing the health impacts of climate change as the justification for the need for action in the near term, in addition to the economic benefits. In particular, he would say that it is not necessary to choose between the health of our children and the health of the economy (Obama, B., 2014). Although the EPA Administrator began discussing the public health rationale for addressing climate change in the beginning of the Administration, the other agencies began using messaging on the public health impacts of climate change after the President announced the Climate Action Plan.

President Obama's messaging on the health impacts of climate change grew while Americans' concern about these impacts increased. This was informed by and reinforced through polling (Maibach, 2010; Myers, 2012). In just one year, Americans' concerns of the public health impacts of climate change increased from March 2015, when 58 percent of Americans thought climate change was a health issue, to 62 percent in November 2016 (Leiserowitz, 2017). In particular, Americans were concerned about respiratory impacts of climate change in children (Leiserowitz, 2014). Socioeconomic groups that were the most vulnerable to climate change, *i.e.*, low-income and infirm Americans, accurately self-identified as being more at risk to the impacts of climate change (Akerlof, 2015).

President Obama launched a multipronged initiative to educate Americans about the connection between climate change and health and to decrease the public health risks of climate change. This initiative was reinforced by several ongoing data-driven peer-reviewed scientific studies that provided evidence that the health impacts of climate change in the United States could not be avoided (Luber G, 2014; U.S. EPA (2017). During his tenure, the Administration also published new environmental health literature building the case that climate change was impacting this generation (USGCRP, 2016; U.S. EPA. 2015). Within academia, as shown in Figure 5, the number of public health publications on the topic *health effects of climate change in the United States* also increased from 9 in 2008 to 75 in 2016 (National Library of Medicine, 2020).

Figure 5. Peer-Reviewed Publications on the Health Effects of Climate Change in the United States



Source: PubMed, 04/29/2018

These findings were communicated through a variety of methods. In the spring of 2014, President Obama conducted his Weekly Address from the Children's National Medical Center, stating that climate change is no longer a distant threat, it has "moved firmly into the present." (Obama, B., May 2014). In the summer of 2014, the White House published a report on the Health Impacts of Climate Change on Americans summarizing how ozone and particulate matter pollution, more extreme-heat events, increasing infectious diseases, higher pollen concentrations, increasing precipitation and flooding are leading to higher rates of morbidity and mortality in Americans, in particular for children, the elderly, and other vulnerable populations (The White House, 2014). In April 2015, President Obama issued a Proclamation declaring the week of April 4, Public Health Week, during that time the Administration held a series of discussions highlighting the public health implications of climate change (Tinker, 2015). President Obama, the Surgeon General, and the Administrator of the EPA met doctors at Howard University to discuss how climate change is affecting American's across the country, in particular children (Tinker, 2015). The conversation brought the abstract issue of climate change into a personal light for both President Obama and the Surgeon General, who shared how air pollution and asthma have impacted them and their family (Tinker, 2015). Later that year, the White House hosted the first Climate Change and Public Health Summit, which included a National Dialogue on Climate Change and Health. The U.S. Surgeon General spoke about climate change as a health issue, stating "climate change poses a serious and immediate . . . threat to public health", including during the launch of EPA's Clean Power Plan (Murthy, 2015). President Obama also worked with public health and medical schools across the country to incorporate climate change into their curriculum and worked to increase access to scientific information on the impacts of climate change.

The Obama Administration also continued to emphasize that climate change would have the largest impact on vulnerable populations and put in place policies to mitigate the effects of climate change on children, tribes, and other vulnerable populations (The White House, 2016). In 2014, the President's Task Force on Environmental Health Risks to Children began focusing on climate change (President's Task Force on Environmental Health Risks and Safety Risks to Children, 2014). In 2016, one of the most comprehensive reports on the impacts of climate change on vulnerable populations in the United States was published (Gamble *et al.*, 2016). Administration officials frequently discussed the need to prevent additional negative health outcomes in children and the elderly in public remarks (McCarthy, 2015).

During the second term, the Obama Administration also launched a series of additional policies and educational activities to decrease the public health risks of climate change, including:

- Creating a National Integrated Heat Health Information System
- Launching a Department of Health and Human Services (HHS) emPOWER Map
- Creating a Climate and Health Innovation Challenge Series
- Establishing a Federal Interagency Working Group on Environmental Justice (EJ IWG) and the Educate, Motivate and Innovate (EMI) Climate Justice Initiative
- Launching a Local Climate and Energy Webcast Series: Climate Change, Heat Islands, and Public Health
- Developing K-12 educational materials on climate change and health
- Establishing a Climate-Ready Tribes and Territories Initiative
- Creating and Revising at *Sustainable and Climate Resilient Health Care Facilities Toolkit*
- Designating May 23-27, 2016, as Extreme Heat Week

(The White House, 2015; 2016).

The heightened attention President Obama put on reducing the impacts of climate change on this generation of Americans also shed light on the importance of ongoing programs to minimize the health implications of climate change, *e.g.*, the Centers for Disease Control and Prevention's Climate Ready Cities Initiative and Building Resilience Against Climate Effects (BRACE) framework, elevating their importance during the appropriations process.

Environmental health literature provided the evidence for President Obama and his Cabinet to educate Americans about the health impacts of climate change on the current generation of

Americans and the urgency to put in place policy to decrease the impacts. In effect, environmental health literature helped provide the moral justification for President Obama to create and implement climate change policy. President-Elect Joe Biden has indicated that he will continue building on the Obama-Biden legacy and implement ambitious climate change policies, including targeted initiatives to decrease the public health risks of climate change (Biden for America, 2020).

Additional literature on the domestic health impacts of climate change will help policy makers to better understand the nuances of the impact that climate change is having on the U.S.population and help mitigate that risk.

Opportunities for Additional Environmental Health Literature to Inform Climate Policy

Additional environmental health literature quantifying the health impacts of greenhouse gas emissions and climate change and the ancillary benefits of reducing carbon pollution and promoting resilience could lead to more durable government policy on climate change domestically (Hong-Mei Deng, 2017). A few policy areas where the lack of environmental health epidemiological studies resulted in less stringent or more broadly applicable regulations are summarized. However, this is only a snapshot of the opportunities for new environmental health studies to support Federal regulations to ensure the government is promulgating the most health protective, lowest cost, and least administratively burdensome regulatory policy.

In at least three cases, the lack of monetized health benefits in a regulation could have resulted in a less stringent greenhouse gas rule. When promulgating greenhouse gas standards for methane emissions from the oil and gas industry and landfills, EPA and BLM did not quantify the health benefits of a decrease in air pollution, instead they provided a qualitative summary of the health benefits. If EPA and BLM had data to quantify the health outcomes avoided from decreases in air pollution, and the benefits were large enough to balance the increase in cost, the agency could have had the opportunity to promulgate a stronger rule. As stated earlier, the issue of not fully monetizing health benefits occurred for other greenhouse gas regulations as well. The following sections identify opportunities where new environmental health literature, data, and methods could improve the quality of greenhouse gas regulatory policy.

Greenhouse Gas Rules with Non-Monetized Health Benefits

While all 11 of the major climate change regulations analyzed in this paper quantified health-related benefits, three did not include the direct health benefits from air quality improvements. In addition, as summarized in Figure 3, many of the RIAs that monetized the direct health benefits lacked data to account for the full health benefit. This presents an opportunity to strengthen the data and the rulemakings. These standards include:

- EPA and NHTSA **carbon pollution standards for trucks and buses** (National Highway Traffic Safety Administration, 2016)
- EPA and Bureau of Land Management (BLM) **methane standards for the oil and gas industry.** The regulations stated that they will have additional benefits, including health benefits from reductions in volatile organic compound (VOC) emissions, HAPs) $PM_{2.5}$, and ozone, but EPA and BLM did not quantify the benefits in the rulemaking (U.S. Bureau of Land Management, 2016).
- The Department of Energy (DOE) publishes dozens of **energy efficiency standards for new appliances**. Although the regulations vary in the amount of carbon emissions that they yield, the greenhouse gas reductions from the appliance standards promulgated will reduce 7 billion tons of greenhouse gases in total (U.S. Department of Energy, 2015).
- Another energy regulation that results in substantial greenhouse gas reductions is **building codes**. Building code revisions are anticipated to avoid hundreds of millions of tons of carbon pollution from decreased electricity demand (Williams, 2014).
- Future EPA greenhouse gas regulations for **refineries, cement, and aircraft**.
- Federal Energy Regulatory Commission **energy proceedings**.

Although the major climate change regulations monetized a portion of the health benefits from air quality improvements, there is an opportunity to augment the benefits assessment and include those due to reduced emissions of additional air pollutants.

The monetized health benefits of climate change regulations are likely larger, but a subset were not quantified. These include the benefits of modifications in HAPs, mercury, hydrogen chloride (U.S. EPA, 2015), and directly emitted $PM_{2.5}$, SO_2, and NO_x, despite the fact that numerous studies are shown that these pollutants have adverse health effects.[13] For example, in the fuel efficiency standards, EPA did not quantify the health benefits of decreases in many HAPs, including benzene. Critics could argue that the quantity of emissions of these pollutants are negligible in comparison to the emissions resulting in indirect $PM_{2.5}$ and ozone formation, which were quantified. For example, $PM_{2.5}$ accounts for less than one percent of emissions from a coal-fired power plant. However, an examination of the small difference in the health benefits and resulting costs in the Regulatory Impact Analysis for repealing and retaining the Clean Power Plan indicate the importance of a full accounting of the benefits of the standard. In addition, EPA's own analysis estimated the rule would result in a 3 percent decrease in mercury emissions when the rule begins, which grows when the rule is fully implemented to a 17 percent decrease,

[13] See for example, U.S. EPA. "Regulatory Impact Analysis for the Clean Power Plan Final Rule." U.S. Environmental Protection Agency. 23 Oct. 2015; U.S. EPA. "Risk and Exposure Assessment for the Review of the Primary National Ambient Air Quality Standard for Sulfur Oxides, External Review Draft." Aug. 2017; U.S. EPA. "Integrated Science Assessment (ISA) for Nitrogen Dioxide - Health Criteria."; U.S. EPA. "Health Effects of Exposures to Mercury."; U.S. EPA. "Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter."

which would have a documented beneficial health impact on Americans (Trasande, 2005; Giang, 2015) . It is highly probable that the quantified health benefits of a 17 percent decrease in emissions would not be negligible and that accounting for the health effects of the abovementioned pollutants would result in a higher probability of retaining the standards.

There is an opportunity for the research community to continue to increase the science-based evidence used to quantify the costs and benefits of the regulations. In order to continue promulgating the most informed climate change regulations that account for the *full* economic benefits of rulemakings, regulators will continue to need environmental health literature evaluating the health impacts of criteria and hazardous air pollutants that are also reduced through greenhouse gas regulations, especially for the largest sources of greenhouse gas emissions.

In addition, each year we learn more about the disproportionate impact of air pollution on communities of color and low-income communities. There is an opportunity to improve the federal and state benefits analysis methods to better account for and avoid impacts, in particular cumulative impacts, in communities that are environmentally and economically disadvantaged.

Although an evaluation of the role that environmental health literature has played in interstate and state climate change regulations is beyond the scope of this paper, it is an important area of study where more robust analysis would result in more informed policy decisions. Existing literature has found:

- California's greenhouse gas cap-and-trade program was estimated to reduce co-pollutant emissions up to 4 percent by 2020 when it was promulgated in 2010 (CARB, 2010). A 2018 publication found that facilities regulated by the cap-and-trade program are "disproportionately located in disadvantaged communities." The publication also found that annual $PM_{2.5}$, SO_2, and NO_x, VOC, and air toxic emissions increased at 44-57 percent of regulated facilities (Cushing, 2018). The California Air Resources Board has not conducted an updated analysis to determine the air quality and health benefits of the cap-and-trade program. However, generally, $PM_{2.5}$, SO_2, and NO_x, VOCs from fuel combustion at stationary sources[14] have decreased since 2010 (CARB, 2018) [15].
- The Regional Greenhouse Gas Initiative (RGGI), an electricity sector greenhouse gas emission trading program in the Northeast has been found to have avoided 537 cases of

[14] Stationary sources in CARB's criteria pollution emission inventory are presented as a proxy for co-pollutant emission from the cap-and-trade program. However, only a portion of the stationary sources included in CARB's criteria pollution inventory are regulated entities subject to the cap-and-trade program. Fuel combustion includes electric utilities, cogeneration, oil and gas production, petroleum refining, manufacturing and industrial, food and agriculture processing, service and commercial and other fuel combustion.
[15] CARB. CEPAM: 2016 SIP - Standard Emission Tool. (2018). Available at https://www.arb.ca.gov/app/emsinv/fcemssumcat/fcemssumcat2016.php. Accessed November 22, 2020.

childhood asthma, 112 preterm births, 98 cased of austin spectrum disorder, 56 cases of term low birth weight, 300 to 830 cases of premature mortality; and more than 8,200 asthma from 2009 to 2014 (Perera, 2020[16]; Manion, 2017[17]).

- The Transportation Climate Initiative (TCI), a multistate effort to create an emissions trading program for transportation fuels, could result in up to 1000 premature deaths and 5,000 cases of childhood asthma in 2032 according to preliminary results (Arunachalam, 2020[18]).

Further, an analysis evaluating the health benefits of national carbon pricing schemes have found that a national cap-and-dividend bill that puts a price on carbon has been estimated to reduce power sector SO_2 and mercury emissions in 2030 95 percent and NO_x emissions 75 percent (Kaufman, 2019[19]). Additional environmental health literature on sectoral and market based greenhouse gas standards and legislation would is needed policy makers to compare the health benefits of multiple different approaches to reducing greenhouse gas emissions.

Most regulatory agencies do not have the capacity to utilize complicated EPA air quality and health impact models. A simpler methodology to calculate health benefits could increase the probability that the DOE, Housing and Urban Affairs, and Interior would include the monetary value of the health benefits of clean energy and climate regulations in their cost benefit analysis. Qualifying the health benefits would provide a more accurate representation of the full costs and benefits of a rulemaking. This metric could have many varieties. At a minimum, EPA should create an Administration wide method for calculating the direct health benefits in air quality improvements for climate change and energy regulations, similar to the standard method for determining the social cost of carbon. Similar to the social cost of carbon, this method shoud have the capacity to estimate the modification in criteria air pollution emissions, mercury, and other HAPs resulting from a decrease in one ton of greenhouse gas emissions or one kilowatt of electricity attributed to power plants across regions in the United States and the resulting health benefits.

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[16] Perera F, Cooley D, Berberian A, Mills D, Kinny P. Co-Benefits to Children's Health of the U.S. Regional Greenhouse Gas Initiative. *Environment Health Perspectives* (2020) 128:7. https://doi.org/10.1289/EHP6706

[17] Manion M, Zarakas C, Wnuck S, Haskell J, Belova A, Cooley D, Dorn J, Hoer M, Mayo L. Analysis of the Public Health Impacts of the Regional Greenhouse Gas Initiative. (2017) Available at https://www.abtassociates.com/insights/publications/report/analysis-of-the-public-health-impacts-of-the-regional-greenhouse-gas. Accessed November 22, 2020.

[18] Arunachalam S. TRECH Project Research Update Preliminary Results - October 6, 2020. Available at https://www.hsph.harvard.edu/c-change/news/trechstudy/. Accessed November 22, 2020.

[19] Kaufman N, Larsen J, Marsters P, Kolus H, Mohan S. An Assessment of the Energy Innovation and Carbon Dividend Act. (2019) Columbia SPIA. Available at https://www.energypolicy.columbia.edu/research/report/assessment-energy-innovation-and-carbon-dividend-act. Accessed on November 22, 2020.

In conclusion, environmental health literature on the impacts of climate change helped provide the legal, economic, and moral justification for President Obama's largest climate change policies, in particular, climate change regulations. The public health justification to advance President Obama's policy agenda was grounded in the fact base of environmental health literature. There are additional opportunities to publish environmental health literature to support climate change regulations. Although some administrations will attempt to roll back President Obama's progress based on political and policy rationale and could successfully rescind a few standards, in the opinion of the author, science will prevail.

Chapter 3. A Literature Review of the Findings and Methodologies Utilized to Evaluate the Monetized Air Quality Benefits of Shifting to Cleaner Electricity Generation Fuels in the United States

Abstract

Increases in the deployment of renewable energy, more utilization of natural gas, and coal plant retirements are modifying the electricity fuel mix in the United States. Numerous studies have evaluated the monetized health benefits resulting from modifications in electricity production fuels under various spatial and temporal durations, in part or in whole. The majority of methods quantified a portion of this transition – the monetized health benefits from air quality improvements, with the most popular tool being BenMap[20]. More recently, authors have built on traditional air quality models to evaluate the health impacts of modifications in energy policy through multi-step models that combine energy dispatch modeling and air quality models. Methods vary from highly technical and data intensive to reduced form models that are less granular[21]. This paper reviews the current methodologies to measure the monetized health benefits of modifications in electricity fuels in the U.S. across various spatial and temporal parameters, compares their findings, and evaluates the variables that are the strongest predictors within each methodology. A thorough review of the literature found that the range of monetized benefits for shifting to solar energy is 1-2.7 cents/kWh and wind energy is 1.3-9 cents/kWh in the United States. Renewable portfolio standards lead to benefits of 3.7-8 cents/kWh. Conversely, the monetized health impact of fossil fuels ranges from 0.1-32 cents/kWh in the United States. The review also found that the pollutant emitted, temperature, power plant location, type of fuel deployed or offset, and type of the health benefits model utilized were the largest predictors of the monetized health benefits.

Introduction

The current literature on the health benefits of modifications in electricity policy fits within three categories: (i) models that estimate the monetized health benefits of modifications in air quality, (ii) models that quantify the impact of modifications in electricity fuels on air quality, and (iii) models that connect the first two types of models to estimate the monetized benefit of modifications in electricity fuel policy. This paper focuses on reviewing the literature in the third category of models to compare the findings, where feasible, and to ascertain the model

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[20] According to U.S. EPA, "BenMAP-CE is an open-source computer program that calculates the number and economic value of air pollution-related deaths and illnesses. The software incorporates a database that includes many of the concentration-response relationships, population files, and health and economic data needed to quantify these impacts." https://www.epa.gov/benmap

[21] See the following for a discussion of reduced form models: IEC prepared for the U.S. EPA. Evaluating Reduced-Form Tools for Estimating Air Quality Benefits. (2019) Available at https://www3.epa.gov/ttn/scram/reports/RFT_Combined_Report_10-31-19_final.pdf. Accessed on 11/21/2020.

parameters that are the strongest predictors of the outcome, in this case the monetized health benefit per kilowatt hour (kWh) of various electricity fuels. The goal of this chapter is to summarize the range of monetized health benefits that result from modification of the U.S. electricity portfolio and to identify the strongest predictors in full form models in order to inform the production of a reduced form model and to help policy makers compare the attributes of various health benefits models.

Methodology

The environmental health and economic literature quantifying the monetized health benefits of shifts to low carbon electricity in the United States were reviewed, summarized, and analyzed using a modified[22] version of the Navigation Guide Methodology developed by Woodruff and Sutton (Woodruff, 2014).

The study questions reviewed included:

- What is the monetized health impact per kilowatt hour (kWh) of changes in renewable and fossil fuel electricity generation in the United States?
- What are the strongest determinants of the monetized health impact of changes in electricity fuel in each econometric and public health model?

A systematic search of the literature was conducted. The literature review was limited to publications that utilized reduced form models to quantify the monetized health benefits of modifications in electricity fuels that were published between 2009 and May 2020. The review was limited to online publications that are available in PubMed, Science Direct, Scopus, and through the UC Berkeley library system.

The following search terms were included: monetized health benefit, energy, public health, air pollution, air quality benefits, air quality, wind, solar, coal, nuclear, natural gas, electricity, renewable, fossil fuel, \$/MWh, \$/ton, $PM_{2.5}$, and ozone.

Each publication was evaluated to identify the variable within each model that is the strongest predictor of the monetized health benefits. The strongest predictors were compared across models with similar methods in order to identify the minimum variables that could be utilized to develop a more streamlined model for policy makers to quickly identify the benefits of modifications in the deployment of various electricity fuels and to inform the design of the epidemiology study in Chapter [4].

[22] The Navigation Guide Methodology has three main steps. "*Specify the study question, Select the evidence, Rate the quality and strength of the evidence.*" The first two steps were followed in this research. The third step was modified in that it was assumed that any peer-reviewed publication found in PubMed, Science Direct, Scopus, and more through the UC Berkeley library system adhered to the criteria for data quality.

Findings

416 studies were identified that fit the review methodology terms, including those identified through a citation review or data-base generated references to similar publications. Following an initial screening, 43 relevant publications remained. Out of the 43 studies, 18 monetized the health benefits of electricity fuels. The results of 18 out of 19 of the publications are summarized in the section *Electricity Fuel Impacts on Monetized Health Benefits*, as one publication (Brown, 2019) did not provide the numerical value of the estimates and instead summarized in graphics.

As explained above, a considerable amount of research has been conducted on aspects of the full method to quantify the monetized health benefit of modifications in electricity generation fuels, *e.g.*, monetizing the health benefits of improvements in air quality and calculating emission factors for changes in electricity generation fuels. Although, these partial findings are not part of the literature review, they are summarized in the first and second section below since they provide insight into the second research question in this analysis: What are the strongest determinants of the monetized health impact of changes in electricity fuel in econometric and public health models?

Air Quality Impacts on Monetized Health Benefits

A number of models exist to evaluate how modifications in air quality affect health outcomes in the United States. Most of this work is conducted to inform the development of the National Ambient Air Quality Standards (NAAQS) for criteria air pollutants. It is beyond the scope of this review to evaluate every air quality benefits methodology. Several publications have quantified the health benefits from reductions of $PM_{2.5}$ and ozone-forming emissions from electric power plants in the United States, in particular reduced form models.[23] Most publications relied on Community Multiscale Air Quality modeling (CMAQ)[24] to calculate improvements in air quality and Pope, 2002 and Laden, 2006 for the premature mortality concentration-response function (Fann, 2012; Fann, 2009; Buonocore, 2014; Penn, 2017).

Electricity Fuel Impacts on Air Quality

Several publications have evaluated the air quality impacts due to wind and solar generation and energy storage in regions of the United States using reduced-form models, often to develop marginal or average emission factors (Valenteno, 2012; Cullen, 2011; Kaffine, 2012;

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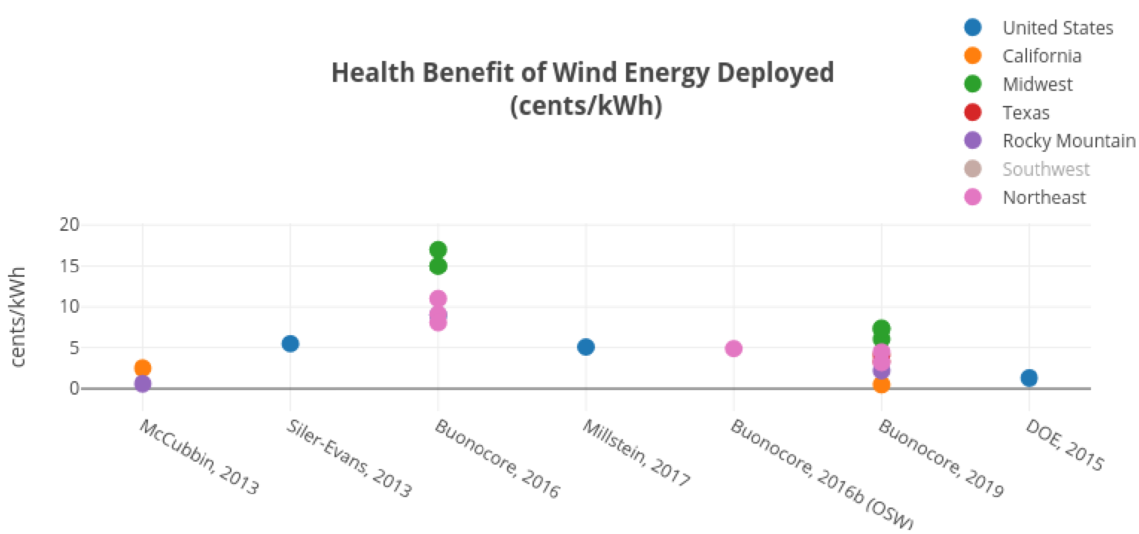
[23] The review is limited to PM2.5 and ozone because previous studies have demonstrated that exposures to these pollutants lead to the largest proportion of health impacts from electric power plants.

[24] According to U.S. EPA, "CMAQ *(see-mak):* an active open-source development project of the U.S. EPA that consists of a suite of programs for conducting air quality model simulations. CMAQ combines current knowledge in atmospheric science and air quality modeling, multi-processor computing techniques, and an open-source framework to deliver fast, technically sound estimates of ozone, particulates, toxics and acid deposition." https://www.epa.gov/cmaq

Katzenstein, 2009; Zhai, 2012; Fisher 2017a; Fisher, 2017b; Meehan, Koomey, 2010; 2012; Driscoll, 2015; Denholm, 2009; Thind, 2017; ISO New England; 2017; Plachinski, 2014; Graff Zivin; 2014; Madaeni, 2013). For example, Zhai found increasing solar deployment 10 percent would result in the largest NO_x and SO_2 emissions per kWh avoided from coal in West Virginia, Indiana, Kentucky, and Ohio (Zhai, 2012). Most authors estimated the air quality impacts using state energy generation and electricity market data at the 15-minute to 1-hour interval and U.S. Environmental Protection Agency (EPA) emission data to estimate the CO_2, SO_2, NO_x emissions offset per MWh of renewable energy generation dispatched to the grid and or fossil fuel generation removed.

Electricity Fuel Impacts on Monetized Health Benefits
A number of full form models exist to determine the entire input chain from modifications in electricity generation fuels to health and economic benefits. A review of the relevant environmental health and econometric literature indicates that the monetized health *benefits* from onshore wind energy deployed onto the electricity grid ranged from 0.5 cents/kWh in California to 17 cents/kWh in the Cincinnati Area and 1.3 – 9 cents/kWh in the U.S. The monetized health benefits of offshore wind range from 2.3 – 7.3 cents/kWh in Maryland and New Jersey (Buonocore, 2016) to 3.3 cents/kWh in Michigan (Chiang, 2016) as summarized in Figure 1.

Figure 1: Review of the Monetized Health Benefit of Wind Electricity Across the United States



The monetized health *benefits* of solar energy are close to those of wind, ranging from 0.4 cents/kWh in California to 19 cents/kWh in the Great Lakes and Mid-Atlantic region and 1 – 2.7 cents/kWh in the United States (Figure 2). A study comparing the monetized health benefits of rooftop and utility scale solar found the benefits range from 0.4-7.9 cents/kWh for rooftop solar and 0.5-7.1cents/kWh for utility scale solar. The results of a recent publication that modeled the health benefits of solar electricity across six Independent System Operators (ISOs) from 2010 to 2017 are available. Figure 3 summarizes the results. The exact values are not provided, but they appear to range from 1.5 cents/kWh in the California Independent System Operator (CAISO) to 5-18 cents/kWh in the Midwest Independent System Operator (MISO) and the Pennsylvania Jersey Maryland Power Pool (PJM) (Brown, 2020).

Figure 2: Review of the Monetized Health Benefit of Solar Electricity Across the United States

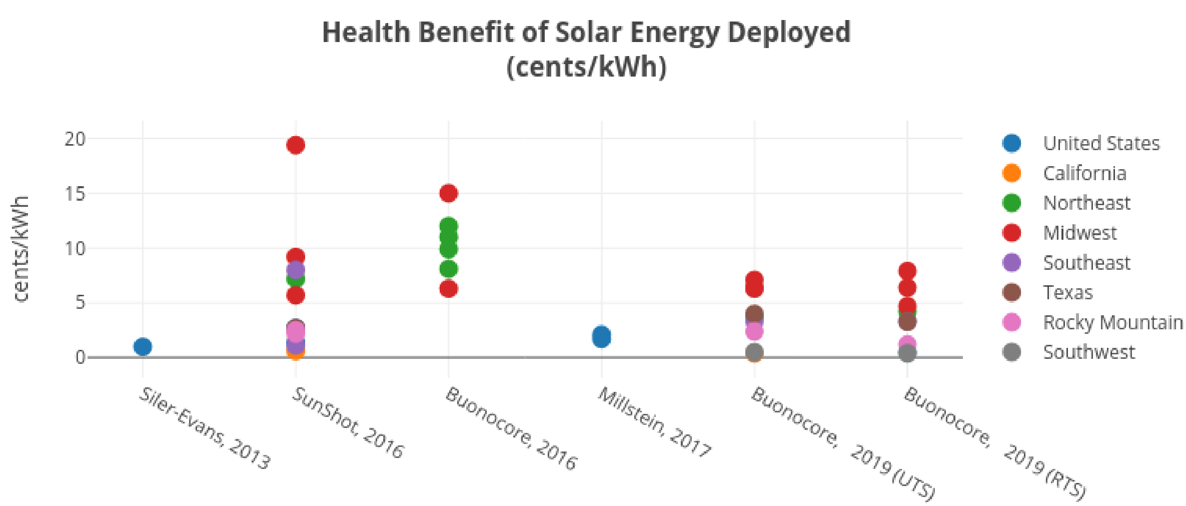
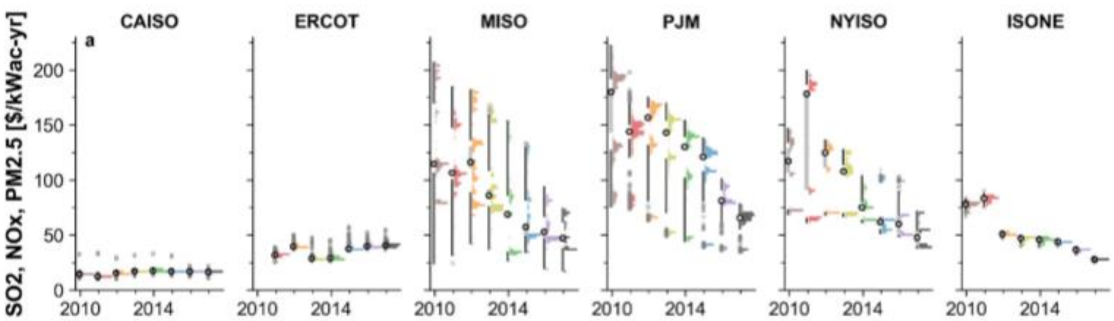


Figure 3. Monetized Health Benefits of Solar Deployment Across Six Independent System Operators (ISOs)[25]



Source: Brown, 2020

29 states, the District of Columbia, and three territories have implemented Renewable Portfolio Standards (RPSs), which generally set a target that a certain amount of electricity is to be generated from renewable electricity fuels in a predetermined time frame (EIA, 2019). Each state defines renewable electricity differently, but it often includes a combination of wind, solar, geothermal, and hydroelectric fuel. Evaluations of the health benefits of RPS policies in the U.S. found a monetized health benefit of 5.3 cents/kWh in 2013 (Barbose, 2016); when projected to 2030, 8 cents/kWh (Dimanchev, 2016); and when extrapolated out to 2050, a health benefit of 2.4-5 cents/kWh (Mai, 2016). These results are shown in Figure 3. A publication projecting the cumulative benefit of a national RPS from 2013-2050 found an average monetized health benefit of $97 billion (Wiser, 2017), while an analysis estimating the social benefit of a 20-50 percent RPS in 2020 in California found $53-149 million in benefits (Rouhani, 2016). These studies did not publish benefits per kWh.

Two separate analyses estimating the monetized health benefit of investments in wind R&D estimated an undiscounted benefit of $8.7 billion from 1976-2008 (Pelsoci, 2010) and $89.5 billion from 1976 to 2017 with a useful life until 2042 (Wiser 2020).

A publication estimating the health benefit of installing 500 MW of utility-scale battery storage in New York found a monetized health benefit of 4.5 cents/kWh for displacing natural gas and 17 cents/kWh for displacing electricity from a fuel oil distillate peaking plant (Gilmore, 2010).

Figure 5 summarizes the monetized health *impacts* of fossil fuel generation. The health *impact* of electricity generation from natural gas is 0.1 – 2 cents/kWh in the U.S, 0.08 – 32 cents/kWh from coal in the U.S. depending on the health benefit model, and 24 cents/kWh from fossil fuels, with a health *impact* of 1 cent/kWh in California to 71 cents/kWh in Maryland. A publication found

[25] Electric Reliability Council of Texas (ERCOT), New York Independent System Operator (NYISO), Independent System Operator New England (ISONE)

the damage per kWh in 1999 from 402 coal plants was between $0.02 - $1.57, with the highest cost in the Midwest (Levy, 2009). Another publication estimated the monetized health benefit of retiring the highest polluting coal-fired power plants and found that NO_x and SO_2 emissions in some counties increased due to other power plants accommodating for their retirements (Venkatesh, 2012).[26]

Figure 4: Review of the Monetized Health Benefits of U.S. Renewable Portfolio Standards

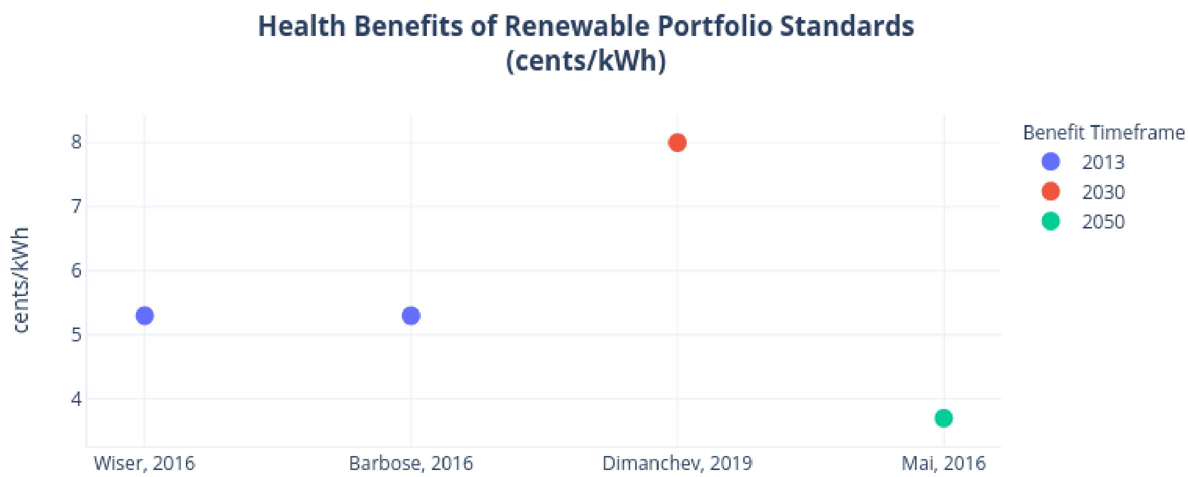
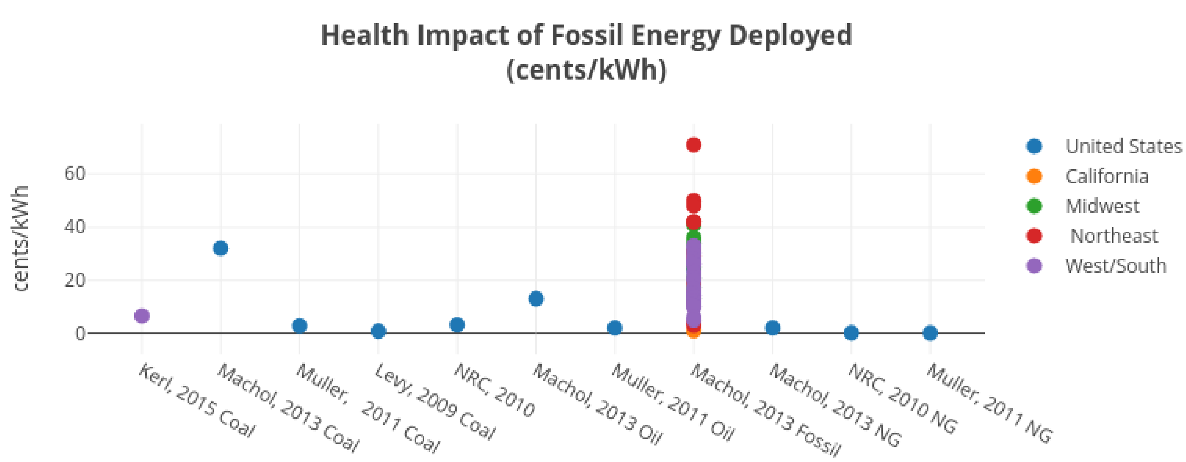


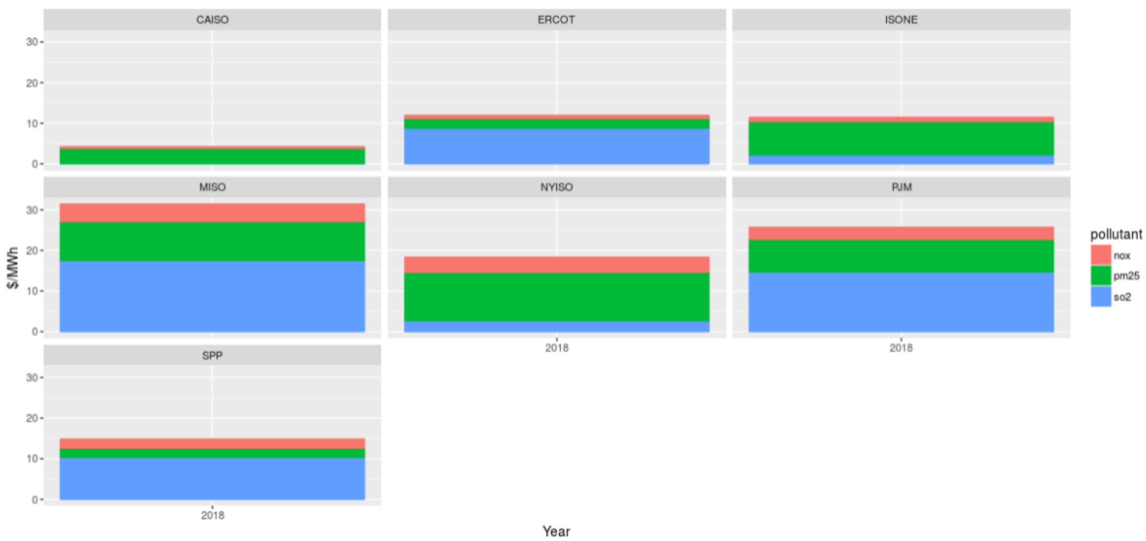
Figure 5: Review of Monetized Health Impact of Fossil Fuel Electricity Across the United States



[26] Publication and supplemental materials did not provide data on monetized benefits, only summarized the data in a graph.

In addition to the results described above, Azendo developed an application to download emission factors that monetized health damages for specific regions in the U.S. (Azevedo, 2019). The results for the monetized health benefits of marginal emission factors for $PM_{2.5}$, NO_x, and SO_2 per Independent System Operator (ISO) in 2018 using the EASIER model are summarized in Figure 6 below. They range from 0.4 cents/kWh in CAISO to 3.1 cents/kWh in MISO. The graph shows that electricity generators in the Midwest ISO emit the largest proportion of SO_2 and NO_x emissions (shown in pink) per MWh of electricity (shown in teal), the generators in ISONY emit the largest proportion of $PM_{2.5}$ (shown in green).

Figure 6. Health Damage per MWh of Electricity Generation in ISO Territories



Source: Azendo, 2019

Strongest Model Predictors of Health and Economic Benefits

Five factors were found to have the largest impact in models evaluating the monetized health benefits of energy policies: type of pollutant, temperature, the electricity fuel modified, power plant location, and type of health benefits model. [According to the literature, the strongest predictor of air quality and economic benefits from wind and solar deployment is the type of fuel that is offset.] Quantity of demand and the frequency of ignition of the power generation facility also have an impact.

Type of Pollution

Air pollution health benefit models have found that reductions of $PM_{2.5}$ and SO_2 emissions result in the largest health benefits. One publication determined that primary SO_2 from power plants that formed $PM_{2.5}$ and SO_2 and NO_x forming ozone, was responsible for 77 percent of premature mortality (Penn, 2017). Another found 77-83 percent of the monetized benefits was due to SO_2 emissions, while ozone forming NO_x only contributed to 4-7 percent of the benefits (Barbose, 2016). An evaluation of the determinants of all U.S. sources of $PM_{2.5}$ emissions on a variety of health outcomes found carbonaceous particles to be the strongest predictor of adverse health outcomes; SO_2 was the second most effective predictor in (Fann, 2009). When only evaluating $PM_{2.5}$ emissions in the Mid-Atlantic and Great Lakes regions, primary $PM_{2.5}$ and SO_2 are the largest contributors to mortality from power plants in 2005 (Buonocore, 2014).

Reduced $PM_{2.5}$ and SO_2 are also the strongest predictors when evaluating the health benefits of wind and solar deployed in the U.S., however, primary SO_2 is a larger driver of health benefits per kWh. Millstein found that the largest per MWh decrease in health outcomes resulted from decreases in SO_2, followed by $PM_{2.5}$, and NO_x (Millstein, 2017). A Department of Energy publication evaluating the projected health benefits of increased solar deployment also found that SO_2 reductions were responsible for 61 percent (AP2), 73 percent (EPA high) and 68 percent (EPA low) of the monetized benefits, depending on the health benefit model (SunShot, 2016). This suggests that when designing a reduced-form model, emissions from NO_x, NH_3, and VOCs, which are traditionally evaluated, might not be necessary to include in order to capture the majority of the monetized health benefits.

Location

According to the literature, mainly three publications, the location of a power plant appears to be one of the strongest indicators of premature mortality. The location factors that result in the largest contribution of premature mortality in health benefits models include:

- Electricity generating units (EGUs) upwind of large population centers (Penn, 2017);
- Within 100 km of a population center in the case of primary $PM_{2.5}$ and SO_2 forming secondary $PM_{2.5}$ (Buonocore, 2014);
- Population centers 100-500 km east of a power plant for primary $PM_{2.5}$ and SO_2 and NO_x forming secondary $PM_{2.5}$ (Buonocore, 2014); and
- Population centers 500-2000 km east of a power plant for SO_2 emissions (Buonocore, 2014).

One publication found that more than 50 percent of premature mortality from power plants was attributed to eight states with coal plants upwind from large population centers, Ohio, Indiana, Pennsylvania, Kentucky, Georgia, Michigan, West Virginia, and Florida (Penn, 2017). Millstein also observed a large regional variation in pollution offset, with more pollution reductions in the central and northeast part of the U.S. than in the west (Millstein, 2017). Barbose found the largest monetized health benefits from renewable portfolio standards were in the eastern United States due to larger populations centers and higher emissions from power plants (Barbose, 2016). When evaluating solar deployment in 2014, the Department of Energy found the largest monetized health benefits in the Great Lakes and North Atlantic Region (SunShot, 2016).

This finding is likely due to two factors. Emissions from power plants in close proximity to a population center are more likely to result in a larger number of adverse health outcomes. As discussed below, coal power plants result in the largest health impacts. Therefore, a state with a higher percentage of electricity production from coal will have more health impacts in models of reduced pollutant emissions. In fact, one publication found that the strongest predictor of premature mortality from power plant emissions is primary emissions of SO_2 from coal-fired power plants, which form $PM_{2.5}$, which are upwind of large population centers (Penn, 2017). Reduced-form models should include state-level resolution, at a minimum, and when possible 100-km resolution. In addition, any analysis of the national health benefits of modifications in energy policy should include the central and northern U.S. and state-level models for Ohio, Indiana, Pennsylvania, Kentucky, Georgia, Michigan, West Virginia, and Florida.

Type of Fuel

Models evaluating the emissions, health, and economic benefits of deploying wind and solar electricity in the U.S. have shown that wind electricity results in more emission reductions per kWh than solar. Millstein's publication relied on EPA's AVERT to determine emission reductions from the deployment of wind and solar in the U.S. and found that wind generation offset more total and per MWh $PM_{2.5}$, SO_2, and NO_x emissions than solar (Millstein, 2017). Another publication that used APEEP to evaluate the health benefits of reducing $PM_{2.5}$, SO_2, and NO_x emissions also found that wind generation offset more emissions than solar, due to the ability of wind to put more energy onto the grid during the night when coal is on the margin (Siler-Evans, 2013). This is the most pronounced in Virginia and Maryland (Silver-Evans, 2013). These studies do not take into account the role of energy storage, which could very much change the emission and in turn health benefit of wind relative to solar if the solar energy was stored and dispatched during the night.

The finding that emission reductions are larger from wind deployment due to its ability to offset coal during night-time hours was reinforced in a publication evaluating the type of emissions offset from wind electricity. One publication, which estimated the CO_2, SO_2, and NO_x emissions offset by wind generation in ERCOT, MISO, and CAISO power dispatching regions, observed that the percentage of coal in the regions generation mix was the largest determinant of the emissions offset by wind (Kaffine, 2012). More coal in a region's generation mix resulted in larger reductions in pollution, in particular SO_2. Cullen also found that although wind generation displaced more MWh of gas powered EGUs than coal, the first four coal-fired power plants displaced by wind generation accounted for all of the SO_2 emission reductions (Cullen, 2013).

Assertions by numerous authors that coal power plants are responsible for the majority of the health impacts were reinforced in Machol, 2013. This paper reported the monetized impacts of

$PM_{2.5}$ emissions from coal (32 cents/kWh) to be more than 10 times that of natural gas (2 cents/kWh) (Machol, 2013). A comparison of the health impacts of fossil fuel generation per state finds that Maryland, Pennsylvania, Ohio have the largest health impacts per kWh of fossil fuel generation, while California, Maine, and Connecticut have the smallest health impacts, and New Jersey is at the median (Machol, 2013). California has nearly no coal power generation sources. Therefore, when prioritizing inputs for a reduced-form model to determine health impacts of emission reductions, information on coal electric generating units (EGUs) should take priority over natural gas EGUs.

Coal emissions offset from nuclear power emissions require unique attention. One publication found that the closure of nuclear plants in the 1980s did not result in an increase in SO_2 emissions when coal generation increased, mainly due to voluntary measures taken by the power plants to reduce SO_2 emissions (Severnini, 2017). Therefore, it is important to include policy interventions in models when possible.

Biomass generation can confound the results of renewable energy deployment. One publication found the few states that allow biomass to achieve RPS compliance resulted in a small increase in emissions, but this was offset by decreases in emissions from other states (Wiser, 2016).

Temperature

Temporal variation is also a strong predictor of air pollution fate and transport and in turn premature mortality. Publications have found that both the month and the time of day affect the health impacts. Penn, 2017 found that primary SO_2 leads to five times higher premature mortality attributed to the indirect formation of $PM_{2.5}$ in July compared to January (Penn, 2017). Additional authors observed this finding and variation in the time of day when evaluating the health impacts from individual power plants. A publication modeling the hourly health impact per kWh of generation from $PM_{2.5}$ emissions at the Bowen coal power plant in Georgia found that in July at 8 and 9 pm the monetized health impact is nearly three times (more than 12 cents/kWh) the health impact/MWh from 6 – 10 am (approximately 4 cents/kWh) (Kerl, 2015). The health impacts per ton were also substantially larger in July than January (Kerl, 2015). The authors attribute these hourly differences to modifications in the formation of $PM_{2.5}$ from sulfate emissions. Primary SO_2 emissions result in higher levels of $PM_{2.5}$ in warmer months.

Health Benefits Model

When evaluating the input for a reduced-form model or comparing the health benefits of modifications in electricity fuels between studies it is imperative to consider the type of health benefits model employed. The four commonly used health benefits models generate distinct results. A publication that quantified the health benefits of emission reductions using four health benefits models indicates that, with consistent emissions, EPA's COBRA[27] results in the largest monetary benefits followed by EPA's benefit-per-ton[28], EASIUR[29], and APEEP[30] (Millstein, 2017). Another earlier study that evaluated the health benefits of three of the models found corresponding results (Barbose, 2016). EPA's COBRA resulted in the largest health benefits, followed by EPA's benefit per ton method and APEEP 2 (AP2) (Barbose, 2016). A third study that used National Renewable Energy Laboratory (NREL)'s Renewable Energy Deployment System (ReEDs) to project emission reductions from solar deployment also found that EPA's benefit-per-ton estimate resulted in more health benefits than AP2 (SunShot, 2016). One reason for the lower health benefits from APEEP and AP2 could be that APEEP allows the user to assess the marginal impact per source, not just the average impact (Muller, 2011).

Quantity of Demand

The quantity of electricity demand can also be a determining factor in the amount of emissions offset. A study evaluating the emissions offset from wind generation in the Electric Reliability Council of Texas (ERCOT) found that one MWh of wind energy on the margin offsets more SO_2 emission when demand is below 40,000 MWh and when coal generation is the energy fuel that would be offset (Novan, 2015). This study also found that the emissions offset from wind energy that comes onto the grid later in the ERCOT dispatch order results in more emission reductions. In particular, one MWh of wind energy from the last wind turbine added to the grid reduces 20 percent more NO_x and 56 percent more SO_2 than one MWh from the first wind turbine (Novan, 2015).

Type of Emission Factor

A recent analysis of damage estimates based on PJM found that using average emission factors for avoided fossil fuel, instead of including renewable electricity generation sources and other non-emitting technologies in the emission factor, overestimates monetized health damages 63 percent (Donti, 2019).

Frequency of Plant Ignition and Type of Dispatch

Additional factors that are more difficult to include in reduced-form models also impact the health benefits from modifications in electricity fuels. A study that modeled electric generating units in Illinois found that an increase in the amount of thermal power plant startups due to

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[27] According to EPA, "EPA's CO–Benefits Risk Assessment (COBRA) screening model is a free tool that helps state and local governments . . . [e]stimate the economic value of the health benefits associated with clean energy policies and programs to compare against program costs." https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool

[28] EPA benefit-per-ton estimate utilizes BenMAP. https://www.epa.gov/benmap/reduced-form-tools-calculating-pm25-benefits

[29] "The Estimating Air pollution Social Impact Using Regression (EASIUR) model is an easy-to-use tool estimating the social cost (or public health cost) of emissions in the United States. The EASIUR model was derived using regression on a large dataset created by CAMx, a state-of-the-art chemical transport model. The EASIUR closely reproduce the social costs of emissions predicted by full CAMx simulations but without the high computational costs." https://www.caces.us/easiur

[30] According to Nick Muller, "The Air Pollution Emission Experiments and Policy analysis (APEEP) model is an integrated assessment model that links emissions of air pollution to exposures, physical effects, and monetary damages in the contiguous United States. The model and its updated version, AP2, have been used in many peer-reviewed publications." https://public.tepper.cmu.edu/nmuller/APModel.aspx.

deployment of wind energy can contribute between 2.5 – 35.7 percent of total emissions, indicating the frequency of startups should be factored into emissions scenarios (Valenteno, 2012). Similarly, Madaeni found natural gas plants in Texas used to backup wind power could lead to an increase in emissions when the plant is not running at full capacity (Madaeni, 2013). However, the natural gas plants displace coal, resulting in a net decrease in emissions (Madaeni, 2013).

Discussion

A review of the current literature found that the monetized health benefits of wind and solar energy in the U.S. vary nationally, with wind resulting in moderately larger benefits due to its ability to generate energy at night when coal is on the margin in most parts of the country. There is substantial geographic variability in the monetized health benefits of deploying renewable energy, with the central U.S. and the northeast receiving the largest benefit per kWh deployed and California receiving minimal benefits per kWh. This is again determined by the regions where the highest proportion of energy that is on the margin is coal, with regions where a higher proportion of electricity production is from coal resulting in a larger benefit from deploying renewables. These findings suggest that when considering how to develop a reduced-form model for national modifications in electricity policy or conducting epidemiology studies on the health impacts of shifting in electricity fuel, a model that focuses on the central and northeastern U.S. could be representative of the upper bound of the national benefit. It also suggests that policy makers with the goal of reducing air pollution nationally should consider prioritizing deploying renewable energy in the central U.S. and the northeast.

This review identified eight parameters that should be considered when developing a reduced-form model to estimate modifications in electricity fuels and conducting epidemiology studies. Five of the parameters are anticipated to be necessary to accurately quantify the monetized health benefits from modifying electricity generation fuels and have the largest impact on the results – type of air pollution offset, location, temperature, type of fuel offset, and the type of health benefits model. Within these parameters the qualities that lead to the largest health benefits are modifications in electricity fuels which decrease SO_2 and $PM_{2.5}$ emissions from coal power plants that are located within 2000 km upwind or west of a large population center in the central or northeastern United States in the summer utilizing EPA's COBRA to determine the monetized health benefit.

The most recent full-form analyses have averaged the results of three to four different types of health benefits models when estimating the value of the health outcomes avoided due to the deployment of renewable energy (Millstein, 2017; Wiser, 2016). This approach is cumbersome and time intensive for policy makers and the private sector. The level of detail required for full-form models might not be necessary for the purpose of estimating health benefits and comparing various policies.

In summary, the strongest predictor of the monetized benefit from modifications in energy policy is the reduction of coal-fired electricity. Effective reduced-form models to estimate health benefits and epidemiology studies should prioritize this variable.

Chapter 4. Estimating the Impact of Shifting to Low Carbon Electricity on Mortality in the Medicare Population using Energy Indicator Variables

Abstract

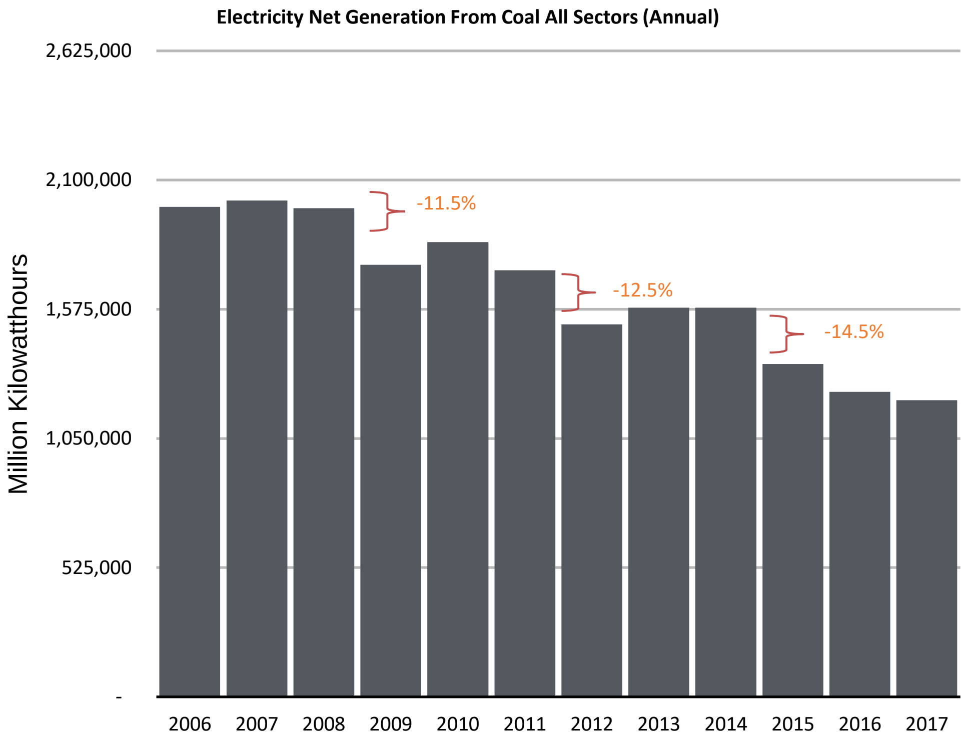
Between 2011 and 2012 coal-fired electricity generation dropped by 12.5% in the United States, signifying one of the two largest decreases in net generation of coal in at least a decade. Although there is substantial literature estimating the health benefits of the transition to low carbon electricity using energy and economic dispatch modeling and analyses of the national and global burden of disease attributed to air pollution from power plants, there are no national epidemiology studies measuring the direct statistical association between shifting to low carbon energy generation and health outcomes. This study takes advantage of the coal retirements from 2011 - 2012 in order to evaluate the health implications of decreasing the generation electricity from coal-fired power plants on the Medicare cohort. This research is the first national epidemiology study examining the direct association between a decrease in the generation of traditional high carbon electricity and mortality. The association between a decrease in megawatt hours (MWh) of high carbon electricity generation fuels in the United States and a change in premature mortality of 341,637 unique Medicare enrollees was tested. The study evaluated the association between a decrease in MWh of coal generation in counties categorized by three indicator variables, 1) absolute decrease in MWh, 2) percent decrease in MWh, and 3) percent decrease in emission-adjusted MWh. The coal plants were located in 492 counties during the period from 2011 to 2012, when one of the largest shifts to low carbon electricity fuels in U.S. history took place. A difference-in-difference (DID) approach was utilized to compare the three exposure metrics to annual mortality in the Medicare cohort. The analysis was conducted at the county level. The 492 counties were then assigned to three sets of intervention and control groups based on their level of exposure, defined as MWh of coal generation. The three sets of exposure metrics and corresponding analyses include: decrease in MWh (Analysis 1), percent decrease in MWh (Analysis 2), and percent change in SO_2 per MWh (Analysis 3). No statistically significant change in mortality in Medicare enrollees was found when comparing the three intervention groups to the control groups and adjusting for confounding. The three indicator variables analyzed yielded the following results. The difference between annual mortality in 90 counties that observed a large decrease in MWh and SO_2 adjusted MWh between 2011 and 2012 and 90 counties that observed small decrease or no change in the corresponding exposure metric was less than one percent (Analysis 1, $\beta = 0.14\%$, 95% CI -0.17 - 0.45, Analysis 2, $\beta = -0.024\%$ 95% CI -0.32 - 0.28; Analysis 3, $\beta = -0.21\%$ 95% CI -0.073 - 0.49). This research provides further evidence supporting the need to conduct multi-step analyses to determine the health effects of energy policy interventions.

Background

Between 2011 and 2012 coal-fired electricity generation dropped by 12.5% in the United States (EIA, 2013). Figure 1 indicates that this time period ushered one of the two largest decreases in net generation of coal in at least a decade. The shift was due to three main factors. One, in 2009, natural gas prices dropped from $8.86 per million Btu to $3.94 per million Btu (EIA, 2018). The drastic decrease in the price of natural gas made it competitive with coal for electricity generation, which has continued to the present day. Two, in 2009 President Obama and Vice President Biden made the largest investment in renewable energy and energy efficiency in U.S. history through the Recovery Act, providing $90 billion to advance renewable energy and energy efficiency and helping to make renewable electricity sources more competitive with fossil fuels. Three, there was regulatory pressure to clean up or retire coal plants. For example, EPA's 2012 Mercury and Air Toxics Standard (MATS), required power plants to reduce their mercury and air toxics emissions by 2016. Although the rule was not finalized until 2012, industry had full visibility that the rulemaking was coming for years and, as indicated in Figure 1, many owners of coal plants decided that it was more economical to close in 2011 than to retrofit. [31] These factors created a natural intervention that can be used to test the association between a decrease in electricity generated from coal-fired power plants and premature mortality in the United States. This research takes advantage of the coal retirements from 2011 - 2012 in order to evaluate the health implications of decreasing the generation electricity from coal-fired power plants on the Medicare cohort.

[31] Although a larger decrease in coal generation occurred from 2014 – 2015 than 2011 – 2012, the 2014 timeframe intervention was almost entirely due to the MATS rulemaking. 2011 – 2012 was selected for this research to evaluate a larger intervention that included the Recovery Act and the decreasing price of natural gas. Both of which did not put as much downward pressure on the coal-fired powered plants in the United States in the 2014 timeframe.

Figure 1. Decrease in Net-Generation of Coal from 2006 - 2017



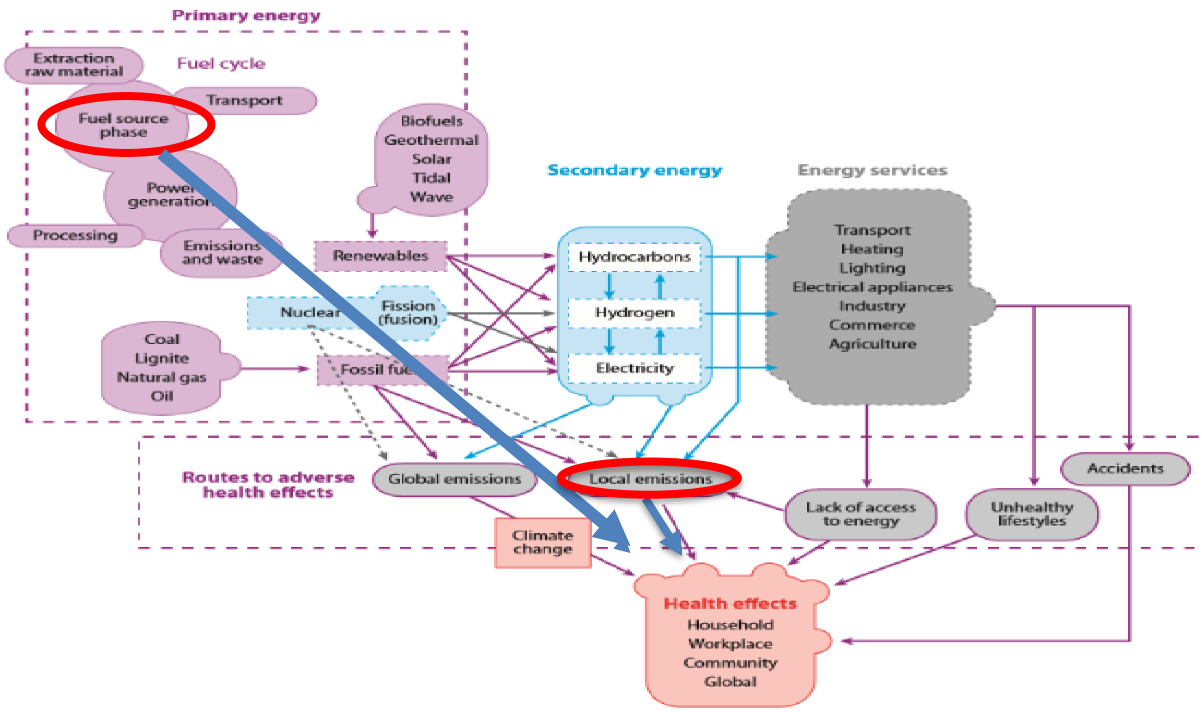
Source: EIA, 2020

Although there is substantial literature estimating the health benefits of the transition to low carbon electricity using energy and economic dispatch modeling and analyses of the national and global burden of disease attributed to air pollution from power plants, which are discussed in Chapter 3, there are no national epidemiology studies measuring the direct statistical association between shifting to low carbon energy generation and health outcomes. That is, where the exposure metric is megawatt hours (MWh) of various sources of electricity fuels, such as coal, instead of pollution.

Traditional epidemiology practice strives to "test" the statistical association between the most accurate exposure variable or exposure indicator and the health outcome. Local emissions and ambient concentrations are the most representative of an individual's direct exposure to the pollutant causing the harm, e.g., $PM_{2.5}$.

Figure 2, a modification from Smith et al., provides a visual summary of the difference between the exposure metric in current epidemiology studies, local emissions, and the exposure metric evaluated in this research, MWh of electricity generation (Smith, 2013). The red circle in the bottom-center of the figure and the blue arrow signify the direct link between exposure to local emissions and health outcomes in most epidemiology studies. The red circle in the top-left of the figure and the blue arrow indicate the longer pathway between fuel sources and power generation to health effects being evaluated in this research.

Figure 2. Energy Exposure and Health Outcome Pathway



This research seeks to test whether there is a statistically significant association between MWh of electricity fuels and a health outcome for two reasons. First, to add to the vast epidemiological literature on air pollution and health and evaluate if an alternative indicator exposure, MWh, is an adequate determinant of exposure to power plant emissions and associated to changes in health outcomes; specifically, to address methodological weaknesses due to lack of source apportionment in air pollution epidemiology studies. Two, to test whether an easy to understand energy metric, MWh, can be used to help policy makers with no training in public health to quickly evaluate the health implications of energy policy.

Epidemiology Rationale for Research

Previous studies have found that power plants and power plant emissions increase mortality and other health outcomes, which are discussed briefly (HEI, 2016; Li, 2014; Henneman, 2019; Amster, 2019; Strasert, 2019; Peterson, 2020). Henneman, Choriat, and Zigler evaluated the association of ZIP code-level $PM_{2.5}$ and Hyads, a unique metric for exposure to coal-fired power plant emissions, which is based on a combination of continuous emission monitoring and air particle trajectory and dispersion modeling. These two metrics were compared to 10 health outcomes in Medicare enrollees between 2005 and 2012 (Henneman, 2019). The authors found a strong association between both $PM_{2.5}$ and coal power plant exposure (Hyads) to cardiovascular disease, cardiovascular stroke, heart failure, ischemic heart disease, and respiratory tract infection. A very small association was found between the exposure variables in all-cause mortality and the authors concluded “that mean effects of exposure reductions have little effect on changes in all-cause mortality.”

Amster and Levy conducted a systematic review of the impact of coal power plant emissions on children’s health (Amster, 2019). The authors identified 17 relevant epidemiology studies. Only two of these studies were on populations in the United States (Yang, 2017; Ha, 2015). The authors found that coal-fired power plant emissions had a statistically significant harmful effect on pediatric neurodevelopment, birth weight, and pediatric respiratory morbidity. Several weaknesses were identified in the 17 studies they reviewed, including lack of source-apportionment and adequate controls for confounding from socioeconomic status.

Strasert, Teh, and Cohan used photochemical modeling to project the changes in $PM_{2.5}$ and ozone and associated health impacts from the closure of 13 coal-fired power plants in Texas (Straset, 2019). They found a decrease of up to 0.9 ug/m^3 of $PM_{2.5}$ and 3.3 ppb of ozone. The largest decrease in mortality from $PM_{2.5}$ ranged from 177 – 81 deaths/yr for W A Parish and Big Brown power plants. A limitation of the study was the decision to use BenMap to estimate the health impacts instead of running their own epidemiology model that could have controlled for confounding variables in the analysis.

There is a small and growing amount of literature on changes in mortality and other adverse health outcomes associated with power plant retirements or retrofitting to cleaner fuel sources. These publications have used proximity to the power plant that retired as an indicator of exposure (Yang, 2017; Casey, 2018a; Casey, 2018b; Casey, 2020). For example, Casey et al. found an increase in fertility rates and a decrease in preterm birth rates among California mothers following the retirement of coal- and gas-fired power plants within 5 and 10 kilometers of their residence in California (Casey, 2018). More recently, Casey found an association between the retirement and conversion to natural gas or the retrofitting of four coal-fired power plants in Kentucky and asthma hospitalization and emergency room visits from 2013 - 2016. These studies employ a variety of methodological techniques to test the best approach in this emerging field of literature. The main weakness of all these studies is the small geographic scope of the analysis. They are all limited to one state or region and therefore cannot be generalized at a national level.

Policy Rationale for Research

As described in Chapter 2 and 3, environmental health literature, and epidemiology studies in particular, are important to the implementation of sound climate change policy in the United States. Environmental health literature provided the legal foundation for regulating greenhouse gases through the Clean Air Act and environmental health literature provided the information necessary to build the economic case for EPA to promulgate greenhouse gas standards. In fact, four of the eleven Obama-Biden Administration's major climate change rulemakings would not have been cost-effective without monetizing the health, environmental, and societal benefits.

The process of determining the health benefits of climate change policies is a data intensive process that requires substantial resources and expertise. Currently, there is not an easy-to-understand metric or method for policy makers to use to determine the health benefits of decreasing the electricity generation from coal plants or increasing the generation of cleaner electricity fuels. Instead policy makers must rely on summaries of complicated models, experts, and consultants to deduce the health implications of policy interventions.

The goal of this research is to test whether a simpler metric, such as the change in megawatt hours of electricity generation at coal-fired power plants, could be used as an accurate quick and easy metric to help estimate the health impacts of policies designed to promote clean electricity fuels.

For example, in an ideal scenario, high level climate and energy policy makers, with no expertise in public health, sitting around a table making the final "call" on whether to select a more or less stringent option for a clean energy standard could deduce that a more stringent option that decreased coal generation 1 million megawatt hours would prevent 1000 premature deaths, while the second option would only decrease 500,000 MWhs and prevent 500 premature deaths. In order for this type of analysis to be possible, either an economist would need to design a reduced form model as discussed in Chapter 3, or an epidemiologist would publish a study that for every x decrease in MWh of coal generation mortality decreases by y percent. This research begins the process of testing for the latter, by conducting an analysis to detect a direct statistical association between a decrease in MWh of coal generation and mortality using the tools of epidemiology. One of the goals of this research is to inject the findings reported in epidemiology literature on air pollution and health into the daily conversations of energy and climate policy makers.

Research Question and Summary of Design

The following research question is examined in this chapter: Is there a statistically significant association between a decrease in MWh generated from coal-fired power plants from 2011 – 2012 and all-cause mortality in the Medicare cohort in the United States?

The exposure metric of megawatt hours was selected as an indicator variable to determine if a decrease in air pollution from shifts to low carbon electricity fuel sources is associated with a decrease in mortality. This exposure metric is novel because it is untested in the literature, it is well understood by policy makers, and, if a statistically significant association is found, it could facilitate better understanding by decision-makers regarding the policy benefits of reductions in MWh generation by coal-fired power plants.

This study question builds on the existing literature described above and in the previous chapters by combining the lessons learned from state-level publications testing the association between coal retirements and health outcomes, e.g., Casey, 2018, and national-level literature testing the association between air pollution and health, e.g., Henneman, 2019. This research also addresses some of the weaknesses that Amster, 2019 found in their literature review by controlling for socioeconomic status in this analysis. This research is the first national level epidemiology study evaluating the health impacts of decreases in the generation of coal-fired power plants without using modeled emissions in the exposure estimate.

It will make a meaningful contribution to the literature on the public health benefits associated with cleaning up coal-fired power plants and toward low carbon electricity generation. In addition to testing the direct association between shifting to cleaner electricity fuels and mortality in the Medicare cohort, this research could also help to identify a metric that can easily be used to estimate the benefits of policy interventions to decrease electricity generation from coal.

In line with the studies referenced above, this analysis uses a difference-in-difference (DID) approach to test the association between the decrease in megawatt hours of coal-fired electricity generated in the U.S. and the change in mortality of adults in the Medicare Cohort between 2011 and 2012. The DID approach has several advantages. Mainly, it allows for a comparison of two groups before and after an intervention. It assumes that the underlying population characteristics in each group (treatment and control) are similar since the group is being compared to itself through time.

Methods

The null hypothesis of this study is that there is no statistically significant association between a decrease in MWh generated from coal-fired power plants from 2011 – 2012 and all-cause mortality in the Medicare cohort in the United States.

The alternative hypothesis is that there is a statistically significant association between a decrease in MWh generated from coal-fired power plants from 2011 – 2012 and all-cause mortality in the Medicare cohort in the United States.

Data Sources

The Medicare data files included demographic information on race, sex (percent female), and age (mean) per enrollee. County level estimates for poverty and income in 2011 and 2012 were downloaded from U.S. Census.gov Small Area Income and Poverty Estimates (SAIPE) Program (U.S Census, 2011; U.S. Census, 2012).

Study Population

The study population is Medicare enrollees residing in the United States in 2011 and 2012. Medicare enrollees were selected as the study population due to several factors. One, previous literature has observed an association between exposure to air pollution from the power sector and adverse health outcomes. Two, the Medicare population is one of the most documented populations in the United States, with data available to researchers. Three, generally, the Medicare population is representative of the older adult population in the United States. Tables 2, 3, and 4 describe the demographic of the study population.

To access data on the study population, the Limited Data Set of Medicare Enrollees Denominator File was purchased from the Centers for Medicare and Medicaid Services for 2011 and 2012 (CMS, 2019). A data use agreement was signed by UC Berkeley for one year (DUA 52836). The study was approved by the University of California at Berkeley Committee for the Protection of Human Subjects (2019-05-12197) and the Office for Protection of Human Subjects. The files on age, race, gender, county of residence, and date of death of 1,113,375 Medicare beneficiaries in 2011 and 2012 were cleaned. Summary statistics on the Medicare enrollees were compared.

The 1,113,375 individual Medicare enrollee files were merged with county level data of MWh of coal electricity generation and emissions data in 496 counties using Social Security Administration (SSA) codes. As described below, 496 counties (out of 3,006 counties) in the United States that contain a coal-fired power plant that was operating in 2011 or 2012 were included in the study population. One of 496 counties, Denali Borough, did not have any Medicare enrollees and was dropped. A new unique identifier for 20 files that were listed as 0 was added. The resulting 639,091 observations were cleaned to remove repeated values in order to assign the Medicare enrollee identifier and the year as panel data.

The final study population included 639,089 Medicare files for 341,637 individual Medicare enrollees that resided in 492 counties in 2011 and 2012, representing more than 16% of the counties in the United States. The 492 counties were divided into subsets of exposure or treatment counties and unexposed or control counties in three distinct analyses to test the association between the decrease in MWh of coal generation and mortality in the Medicare cohort. Each of the three analyses included approximately 180 counties in total, roughly 90 in the exposed group and 90 in the unexposed group. The mean mortality in the proportion of the entire population analyzed was 6.3% and the mean MWh of coal electricity generation per year was 3,282,207. A summary of the counties in each analysis is provided in Appendix A.

Exposure Assessment

The main exposure metric in this study is MWh of annual coal-fired electricity generation at power plants in the United States. The study includes three sets of intervention and control groups that were classified by their level of exposure. The three sets are shown in Table 1 and described in detail below. One of the three exposure metrics adjusts by air pollution to account for the intra-plant differences in the quantity of air pollution emitted per MWh of generation.

Exposure data was gathered from the Energy Information Administration (EIA) Form 923 and U.S. EPA's Air Market Program. EIA data was examined to determine the change in electricity generation from 2011 – 2012 for the main exposure variable (EIA, 2018a). As stated above, the 2011 - 2012 period was selected as the exposure time frame since a 12.5 percent decrease in annual electricity generation from coal power plants was observed from 2011 to 2012. No washout period was included in this analysis for two reasons. One, there was a substantial difference in the exposure metric between 2011 and 2012. Two, as described above, previous research has shown that there is an association between exposure to air pollution and daily mortality and adverse health outcomes (Di, 2017b).

Electricity Generation Data

To determine the exposed and unexposed counties, the power plants using coal-fired electricity were identified by selecting the AER Fuel Type COL in EIA Form 923 data. The coal-fired electricity generation data from form EIA 923 (PLANT_CODE) was then merged with EIA Form 860 (PLANT_ID) to determine the county where the power plant is located (EIA, 2018b). Coal-powered generation decreased in 363 counties, increased in 75 counties, and remained at constant levels in 22 counties from 2011 – 2012. After cleaning the data[32], 494 counties with data on coal electricity generation were included in the analysis.

Air Pollution Data

One MWh of coal generation will not necessarily result in the same level of pollution, and therefore premature mortality, at all coal power plants. The type, age, and emissions control

[32] Forty-eight power plants were not matched in the 2011 data. Thirty-five power plants were not matched in the 2012 data. The coal export terminals in Form 860 that had zero coal-powered electricity were dropped. The variables representing state coal-fired electricity that were s not reported by the individual plants were also dropped since they cannot be accounted for in this county level analysis.

technology could in turn impact the exposure and be a confounding variable in the analysis. Two approaches were taken to adjust for pollution level per MWh of coal-electricity generated. First, in the case where the exposure metric is MWh, SO_2 emissions were included as a confounding variable in the model. Second, a new SO_2 adjusted MWh exposure metric was created to test the association with mortality in the Medicare cohort. When the second approach was utilized, SO_2 emissions were not tested as a confounding variable in the model. SO_2 emissions were selected as an indicator of mortality related pollution because, as described in chapter 3, SO_2 is one of the strongest predictor variables in determining the health implications of changes in the electricity policy.

To create the SO_2 adjusted MWh exposure metric, coal-powered electricity generation data was linked to SO_2 emissions per power plant in 2011 and 2012. U.S. EPA's Air Market Program was queried for SO_2 emissions using the following filters: *all programs and data sets, 2011 – 2013, all units that use coal as their fuel including those that are retired, long term, and operating* (U.S. EPA, 2019). The data was aggregated to the facility ID level. EPA FIPS codes were cross walked with SSA county codes in order to combine datasets data (NBER, 2012). The resulting variable tons of SO_2 emissions per MWh was generated and the absolute value was used since some of the facilities had negative net annual generation of electricity[33]. EPA emissions data was not available for 145 out of 791 facilities. The average SO_2 per MWh in the county was used for these facilities when aggregated to the county level.

Counties Assigned to Three Intervention and Control Sets

The 494 counties were then assigned to three sets of intervention and control groups based on their level of exposure, defined as MWh of coal generation. The three sets of exposure metrics and corresponding analyses include: decrease in MWh (Analysis 1), percent decrease in MWh (Analysis 2), and percent change in SO_2 per MWh (Analysis 3). Details on the rationale and the exposure metric are provided in Table 1. In each analysis, roughly 90 counties were defined as the intervention group and 90 counties were defined as the control group.

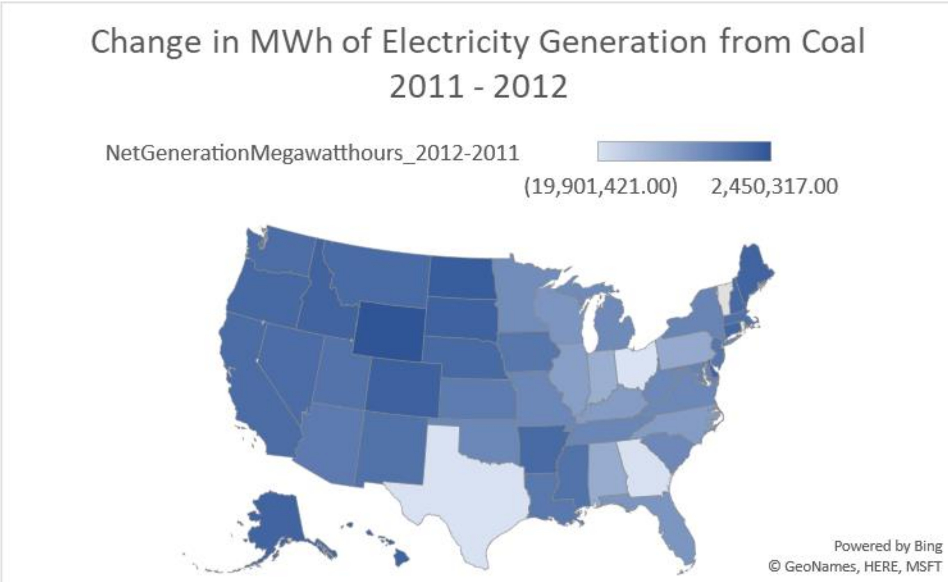
To operationalize this, the raw change in MWh and emissions data was calculated across 496 counties to assign 180 counties to the intervention or control groups in three analyses. A file of the merged energy and air pollution data at the county level was sorted to identify three types of indicators for the change in MWh of electricity generation from coal.

The analysis of EIA data found that the largest decrease in coal-powered electricity generation between 2011 - 2012 occurred in six states. Figure 3 shows the change in MWh in each state. In summary, Texas, Ohio, and Georgia each experienced a nearly 20 million MWh decrease in coal-powered electricity generation between 2011 and 2012. Indiana, Alabama, and

[33] Some of the facilities consumed more electricity than they generated.

Pennsylvania each experienced a more than 10 million MWh decrease in coal-powered electricity generation.

Figure 3. Change in Coal-Powered Electricity Generation per State from 2012-2012



A decrease in more than 1,000,000 MWh of coal generation between 2011 to 2012 in a county was selected as the exposure metric for Analysis 1, which as is shown in Figure 4, was observed in 93 counties. The one million MWh threshold was selected after examining nine quantitative thresholds of exposure in 507 counties[34]. The results are presented in Figure 4. After consulting with the dissertation committee chair, it was determined that the one million MWh threshold would provide the necessary power to test the association and balance the direction from the committee work with a manageable amount of data[35]. In the interest of minimizing bias between the size of exposure groups, a rule of 90 counties in the exposure and unexposed groups was utilized to categorize the counties in the rest of the analyses.

In Analysis 2, the exposure metric tested is county-level percent change in MWh. This metric was included to account for the underlying magnitude of electricity production from coal in each county. Since one MWh from a coal plant with low SO_2 emissions could have different health effects than one MWh of electricity generated from a coal plant with high SO_2 emissions, Analysis 3 tests the association between the exposure metric for the percent change in SO_2 per MWh on mortality in the Medicare cohort.

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[34] 507 counties were included in the initial uncleaned analysis.

[35] Each additional county required merging and cleaning thousands of files.

Figure 4. Size of Decease in MWhs in Counties Evaluated in Study Population

- Decrease > 5 Million MWh: 2 counties
- Decease > 4 Million MWh: 5 counties
- Decrease > 3 Million MWh: 14 counties
- Decrease > 2 Million MWh: 32 counties
- **Decrease > 1 Million MWh: 93 counties**
- Decrease > 0.5 Million MWh: 148 counties
- Decrease > 0.1 Million MWh: 261 counties
- Decrease > 0.05 Million MWh: 281 counties
- Decrease > 0.01 Million MWh: 337 counties

Table 1. Three Sets of Exposure Metrics Evaluated in Study

Analysis	Metric used to Assign Counties	Rationale	Counties in Intervention Group	Counties in Control Group
1	Δ MWh	Test of MWh as a proxy indicator variable for exposure.	92 Counties that experienced a decrease in more than 1,000,000 MWh between 2011 – 2012.	91 counties that experienced a decrease of less than 25,000 MWh or no change in MWh from 2011-12.
2	Percent Δ MWh	Test of percent change in MWh as a proxy indicator variable for exposure.	90 counties that had the largest percent decrease in MWh from 2011 – 2012.	90 counties that had no change in MWH or the smallest percent decrease in MWh from 2011 – 2012.
3	Percent Δ SO_2 / MWh	To test the utility of including pollution level in the exposure metric to account for high and low polluting plants. Instead of adjusting for SO_2 in the model.	90 counties with a large percent decrease in SO_2/MWh from 2011 to 2012	90 counties with a percent increase in SO_2/MWh from 2011-2012

Confounding Variables

This study tests the role of six potential confounding variables: race, sex (percent female), age (mean), median household income (mean), percent poverty, and SO_2 emissions (mean SO_2 / MWh). Individual level data was included for three categories of confounding variables, e.g., race, sex, and age. Area level data at the county level was included for median household income and percent poverty for 2011-2012 from the U.S. Census.gov Small Area Income and Poverty

Estimates (SAIPE) Program. SO_2 facility level data was included for SO_2 emissions when feasible, as described earlier.

Previous studies have found that race, sex (percent female), age (mean), median household income (mean), and other indictors of socioeconomic status can confound the association between air pollution exposure and premature mortality. Consequently, these five variables were tested in the model to determine if they were responsible for a significant amount of the association between the exposure metric and mortality. Race was broken down into seven subcategories to determine if there was a stronger association with certain races. These subcategories, which were predefined in the Medicare data, include: North American Native (NNA), Hispanic, Asian, Other, Black, White, Unknown.

One MWh of coal electricity generation at one power plant can have a substantially different emission profile than one MWh at another power plant. Since mortality is associated with SO_2 and $PM_{2.5}$ emissions (Henneman, 2019), it is important to adjust for high and less polluting coal power plants. SO_2 emissions per MWh of electricity generation was also included in the analyses when emissions was not accounted for in the exposure metric to determine if it is a confounding variable.

A summary of the demographic information in each exposure group is presented in Table 2, 3, and 4.

Statistical Analysis

A difference-in-difference analysis was used to test the association between the decrease in megawatt hours of coal-fired electricity generated in the U.S. and the change in mortality of adults in the Medicare Cohort between 2011 and 2012. The DID approach allows for a comparison of two groups before and after an intervention. It assumes that the underlying population characteristics for each group (treatment and control) are similar since the group is being compared to itself through time (Casey, 2018b).

A linear mixed model clustering for county level effects was used to conduct the DID through the xtreg function in Stata. The panel data was defined by each Medicare enrollee's unique identifier. The DID model used in the analysis was:

Proportion Mortality for Medicare Enrollee x Residing in County y = $\beta 0 + \beta 1 \ x \ Int_{1-3} + \beta 2 \ x \ year + \beta 3 \ x \ Int_{1-3} \ x \ year + Cov, \ Cluster \ (County)$

In the analysis Int_{1-3} is a binary variable identifying if the Medicare enrollee resides in the intervention county for the four analyses. Year is a binary variable identifying if the year is before or after the intervention. $\beta 3$ is the coefficient in front of the interaction term. $\beta 3$ represents the estimate of the difference in mortality in the intervention and control counties before and after the intervention. Cov represents the continuous confounding variables included in the model, age, race, sex, and the absolute value of tons of SO_2 emissions per MWh.

The cluster function ($Cluster\ (County)$) was utilized to add a random intercept to adjust for standard error at the county level. This is important to account for the non-independence of mortality within a county.

To conduct each of the three analyses, the county level control and treatment groups were merged with the corresponding Medicare enrollee date files and confounding variables, *i.e.*, through merging the county level energy and emissions data as described below with individual Medicare enrollee files for 2011 and 2012.

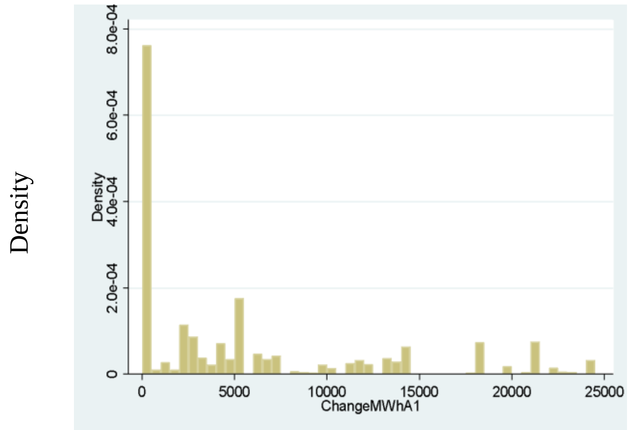
In addition, summary statistics were compared for the intervention and control groups in Analysis 1-3, which are described in the following sections.

Analysis 1. Decrease in MWh of Coal Electricity Generation

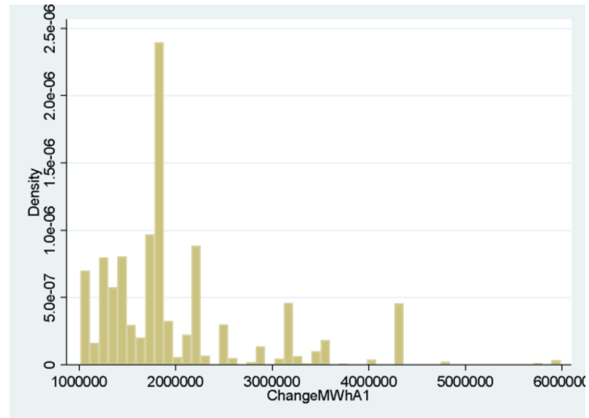
Analysis 1 examined 182 out of 485 counties with MWh data in both 2011 and 2012. The analysis treated 92 counties with a net decrease in MWh of coal generation greater than or equal to 1,000,000 MWh between 2011 and 2012 as the intervention, treatment or exposed population and 91 counties with no change in MWh of coal electricity generation or a decrease in coal generation less than 25,000 MWh between 2011-2012 as the nonintervention or control or unexposed population. The 182 counties in Analysis 1 represented 129,633 unique Medicare enrollees and 224,022 individual Medicare files in 2011 and 2012.

Figure 5 shows the total change in MWh of electricity generation from coal in the intervention and control group. The 182 counties in Analysis 1 represented 129,633 unique Medicare enrollees and 224,022 individual Medicare files in 2011 and 2012.

Figure 5. Total Change in MWh of Electricity Generation from Coal from 2011 to 2012 in Medicare Intervention and Control Groups



Change in MWh in 91 Counties with No Intervention



Change in MWh in 92 Counties with Intervention

Sensitivity Analysis

NO_2 Emissions

To evaluate if changes in mortality were due to transportation emissions, a sensitivity analysis was conducted using the county level average NO_2 concentration measured in parts per billion (ppb). NO_2 concentration was added to the models in Analysis 1-3 (below) to test whether part of the association between the exposure metric and mortality could be attributed to transportation emissions. NO_2 concentration estimates were developed by the Center for Air, Climate and Energy Solutions using v1 empirical models, as described in Kim S.-Y.; Bechle, M.; Hankey, S.; Sheppard, L.; Szpiro, A. A.; Marshall, J. D. 2020 were download at the county level for 2011 and 2012 (CACES, 2020). The data did not include concentrations for Hawaii and Alaska, which we included in the study population.

MWh Exposure Metrics Association to Hyads

The validity of MWh as an exposure metric was also tested against Hyads, an alternative metric of coal fired power plant exposure. Henneman, Choriat, and Zigler created Hyads, a ZIP code-level metric of exposure to coal-fired power plant emissions that is based on a combination of continuous emission monitoring and air parcel trajectory and dispersion modeling. Their research compared the Hyads metric to 10 health outcomes in Medicare enrollees between 2005 and 2012 (Henneman, 2019). As part of the study, the authors tested the correlation between Hyads and annual average $PM_{2.5}$ (Pearson correlation, 0.88) and SO_2 (Pearson correlation, 0.73) concentrations and found a positive correlation.

In this study the correlation of MWh and Hyads was tested utilizing a Spearman correlation test. In order to test the correlation, the MWh and SO_2 / MWh exposure metrics at the county level were merged with Hyads data (Casey, 2020b) for 2012. Summary statistics on the mean Hyads level in each intervention and control group are also presented in Tables 2 - 4.

Results

Comparison of Characteristics of Control and Intervention Groups

Analysis 1. Absolute Decrease in MWh of Coal Electricity Generation

Summary statistics on individual level characteristics and energy and emissions data were compared and are presented in Table 2. The mean age of Medicare enrollees in the control and intervention groups increased by one year from 2011 to 2012. The mean SO_2 emission per MWh of coal generation in the control and interventions groups increased from 2011 to 2012, signifying that each MWh of electricity generation resulted in more pollution. Median household income was slightly lower in the treatment group than the control group. However, percent poverty was consistent between the treatment and control group. The racial distribution of Medicare enrollees largely did not shift between 2011 and 2012 in both the intervention and the control groups. One of the largest differences between the groups was that the percent of black, North American Native (NNA), and other races was substantially higher in the intervention counties, including double for NNA and black.

Table 2. Analysis 1 County and Individual Level Summary Statistics for Decrease in Coal MWh Intervention and Control Groups

	Medicare Enrollees in Control Counties			Medicare Enrollees in Treatment Counties		
	2011	**2012**	**Difference**	**2011**	**2012**	**Difference**
MWh mean (SD)	66,935 (SD 205,048)	60,857 (SD 203,363)	-6078	7,810,850 (SD 5359771)	5,824,204 (SD 5,090,469)	-1,986,646
Mortality (mean)	5.9% (SD 24%)	6.1% (SD 24%)	0.20	6.2% (SD 24%)	6.4% (SD 24%)	0.20
Hyads	0.63 (SD 0.41)	0.43 (SD 0.27)	-0.20	0.88 (SD 0.33)	0.61 (SD 0.23)	-26
Race[36]						
NNA[37]	0%	0%	0	1%	1%	0
Hispanic	2%	2%	0	2%	2%	0
Asian	1%	0%	-1	1%	1%	0
Other	1%	0%	-1	1%	1%	0
Black	8%	8%	0	17%	17%	0
White	87%	87%	0	78%	78%	0
Unknown	0%	0%	0	0%	0%	0
Sex (% female)	58%	58%	0	58%	58%	0
Percent Poverty	15% (SD 5%)	15% (SD 4%)	0	16% (SD 4%)	17% (SD 4%)	1
Median Household Income (mean)	51,682 (SD 11121)	52,707 (SD 11015)	1,025	49,705 (SD 9397)	50,884 (SD 9615)	1,179
Age (mean)	76 (SD 12)	77 (SD 12)	1	76 (SD 12)	77 (SD 12)	1
SO2/MWh (AV, mean tons)	0.016 (SD 0.020)	0.042 (SD 0.15)	0.03	0.0038 (SD 0.004)	0.086 (SD 0.65)	0.08
NO_2 (ppb)	7.4 (SD 2.3)	7.4 (SD 2.3)	0	9.5 (SD 4.5)	9.5 SD (4.5)	0

The decrease in coal electricity generation between 2011 and 2012 in the intervention groups was more than 325 times the decrease in the control group. However, mortality increased by 3.3 percent in the control group and 3.2 percent in the treatment group from 2011 - 2012.

Analysis 2. Percent Decrease in MWh of Coal Electricity Generation

Analysis 2 maintains consistency with the nearly 90 county comparison groups in Analysis 1, while considering the relative change in MWh. The analysis compares the percent change in MWh of coal electricity generation between 90 counties with the largest percent MWh decrease in coal electricity generation (55.80 - 516.49% decrease in MWh) in 90 counties with no change or a small decrease (0 - 8.49% decrease) in MWh of coal electricity generation. The 180 counties in Analysis 2 represented 128,714 unique Medicare enrollees and 239,543 individual Medicare files in 2011 and 2012.

[36] Categories defined in Medicare data.

[37] North American Native (NNA)

Summary statistics on individual level characteristics and energy and emissions data for Analysis 2 were compared and are presented in Table 3. The mean age of Medicare enrollees in the control and intervention groups increased by one to two years from 2011 to 2012. Median household income was slightly lower in the treatment group than the control group. However, percent poverty was consistent between the treatment and control group. The race distribution of Medicare enrollees largely did not shift between 2011 and 2012 in both the intervention and the control groups. Unlike Analysis 1, there was not a substantial difference between the race distribution in the intervention and control group. Similar to Analysis 1, the mean SO_2 emission per MWh of coal generation in the control and interventions groups also increased from 2011 to 2012, signifying that each MWh of electricity generation resulted in more pollution.

Table 3. Analysis 2 County and Individual Level Summary Statistics for Percent Decrease in Coal MWh Intervention and Control Groups

	Medicare Enrollees in Control Counties			**Medicare Enrollees in Treatment Counties**		
	2011	**2012**	**Difference**	**2011**	**2012**	**Difference**
MWh (mean)	3,415,806 (SD 4,439,292)	3,167,112 (SD 4,296,067)	-7%	780,704 (SD 1,027,234)	190,495 (SD 329,040)	-76%
Mortality (mean)	6.1% (SD 24)	6.4% (SD 25)	0.30	6.2% (SD 24)	6.4% (SD 24)	0.20
Hyads	0.70 (SD 0.49)	0.52 (SD 0.34)	-0.18	0.70 (SD 0.46)	0.47 (SD 0.31)	-0.23
Race						
NAA	1%	1%	0	0%	0%	0
Hispanic	2%	1%	0	3%	3%	0
Asian	1%	1%	0	1%	1%	0
Other	1%	1%	0	1%	1%	0
Black	13%	12%	-1	12%	12%	0
White	82%	83%	1	82%	83%	1
Unknown	0%	0%	0	0%	0%	0
Sex (% female)	57%	58%	1	58%	58%	0
Percent Poverty	17% (SD 6%)	17% (SD 6%)	0	18% (SD 5%)	18% (SD 5%)	0
Median Household Income (mean)	48,821 (SD 11095)	49,930 (SD 10714)	1,109	48,398 (SD 9968)	49,282 (SD 10156)	884
Age (mean)	75 (SD 12)	77 (SD 12)	2	76 (SD 12)	77 (SD 12)	1
SO2/MWh (AV, mean tons)	0.0093 (SD 0.0079)	0.020 (SD 0.054)	0.011	0.18 (SD 2.2)	0.23 (SD 1.0)	0.050
NO2 (ppb)	8.1 (SD 2.9)	8.0 (SD 2.8)	-0.1	8.6 (SD 3.3)	8.6 (SD 3.2)	0

MWh of electricity generation from coal decreased 76% in the intervention counties compared to 7% in the control counties. However, mortality increased by 3.3 percent in the control group, similar to the Analysis 1, and 4.9 percent in the treatment group from 2011 - 2012.

Analysis 3. Percent Change in SO_2 Emissions per MWh of Coal Generation

Analysis 3 tests whether 90 counties with a large percent decrease in SO_2/MWh from 2011 to 2012 (-12 – -69,701% SO_2/MWh) observed a different mortality in Medicare enrollees compared

90 counties with a percent increase in SO_2/MWh (11 – 10,161% SO_2/MWh). The counties that observed an increase in SO_2/MWh were included in this analysis since there were only 337 counties with data for both 2011 and 2012. The 180 counties in Analysis 4 represented 148,285 unique Medicare enrollees and 276,230 individual Medicare files in 2011 and 2012.

Summary statistics on individual level characteristics and energy and emissions data for Analysis 3 were compared and are presented in Table 4. The mean age of Medicare enrollees in the intervention groups increased by at least one year from 2011 to 2012, similar to Analysis 1, 2, and 3, but not the control group. Median household income was slightly lower in the treatment group than the control group. However, percent poverty was consistent between the treatment and control group. The race distribution of Medicare enrollees largely did not shift between 2011 and 2012 in both the intervention and the control groups. Similar to Analysis 1, there was a difference between the race distribution for Hispanic and Black Medicare enrollees in the control and intervention groups. However, unlike Analysis 1, the control counties were more diverse than the counties with a large percent decrease in SO_2 emissions per MWh of electricity generation from coal.

Table 4. Analysis 3 County and Individual Level Summary Statistics for Percent Change in Emissions per MWh Intervention and Control Groups

	Medicare Enrollees in Control Counties			**Medicare Enrollees in Intervention Counties**		
	2011	**2012**	**Difference**	**2011**	**2012**	**Difference**
SO2/MWh (AV, mean tons)	0.0075 (SD 0.0070)	0.019 (SD 0.040)	153%	0.11 (SD 1.76)	0.14 (SD 0.81)	27%
MWh (mean)	3649319 (SD 3541112)	2898422 (SD 3725072)	-75,0897	6354357 (SD 5761214)	5066875 (SD 4842757)	-1,287,482
Mortality (mean)	6.3% (SD 24)	6.5% (SD 25)	0.20	6.2% (SD 24)	6.6 (SD 25)	0.40
Hyads	0.88 (SD 0.44)	0.61 (SD 0.32)	-0.27	0.81 (SD 0.36)	0.58 (SD 0.25)	-0.23
Race (Medicare Code)						
NAA	0%	0%	0	0%	0%	0
Hispanic	1%	1%	0	2%	2%	0
Asian	1%	1%	0	1%	1%	0
Other	1%	1%	0	1%	1%	0
Black	17%	17%	0	13%	12%	-1
White	80%	80%	0	83%	84%	1
Unknown	0%	0%	0	0%	0%	0
Sex (% female)	58%	58%	0	58%	58%	0
Percent Poverty	18% (SD 5%)	17% (SD 5%)	0	16% (SD 5%)	16% (SD 5%)	0
Median Household Income (mean)	46,173 (SD 8729)	47,775 (SD 9272)	1,602	50,485 (SD 12279)	51,785 (SD 12605)	1,300
Age (mean)	76 (SD 12)	76 (SD 12)	0	76 (SD 12)	77 (SD 12)	1
NO2 (ppb)	7.7 (SD 2.6)	7.8 (SD 2.6)	0.1	7.5 (SD 3.0)	7.5 (SD 3.0)	0

Despite the fact that the intervention group comprised 90 counties with the largest decrease in SO_2 emissions per MWh between 2011 and 2012, SO_2/MWh increased in both the intervention group and the control group. Part of the rationale for the increase in SO_2/MWh is the metric inself. If SO_2 emissions are held constant, and MWhs decrease, the metric for SO_2/MWh will increase. The average increase in SO_2/MWh in the intervention counties was one-fifth the increase in the control counties. This finding is in line with Analysis 1 and 2, all of which also resulted in an increase in SO_2/MWh within and between the intervention and control groups. Mortality increased by 3.2 percent in the control group and 6.5 percent in the intervention group from 2011 - 2012. Analysis 3 was distinct from the earlier analyses in that the change in mortality was higher in the intervention group than the control group.

Association between Exposure Variable and Health Outcome

Analysis 1. Decrease in MWh of Coal Electricity Generation

Analysis 1 examined 182 counties out of 485 counties with MWh data in both 2011 and 2012. The analysis treated 92 counties with a net decrease in MWh of coal generation greater than or equal to 1,000,000 MWh between 2011 and 2012 as the intervention, treatment or exposed population and 91 counties with no change in MWh of coal electricity generation or a decrease is coal generation less than 25,000 MWh between 2011-2012 as the nonintervention or control or unexposed population. The 182 counties in Analysis 1 represented 129,633 unique Medicare enrollees and 224,022 individual Medicare files in 2011 and 2012.

Table 5 presents the results of the adjusted and unadjusted difference-in-difference estimates for Analysis 1 – 3. In Analysis 1, a decrease in MWh of coal electricity generation from 2011 to 2012 did not result in a statistically significant difference in mortality rate in Medicare enrollees compared to the control group. The adjusted and unadjusted analyses found a small, but not statistically significant, increase in mortality (0.14%, 95% CI -0.17% - 0.45%) for the intervention group. The coefficients did not change substantially after controlling for age, sex, and median household income and clustering at the county level. Despite the large difference in the racial distribution in the summary statistics, race was not a statistically significant predictor in the model and was removed. Percent poverty was also not significant and therefore excluded from the model. When SO_2/MWh was added to the model to adjust for pollution levels per MWh, the coefficient went from positive to negative resulting in a small (-0.052 – -0.053 %, 95% CI -0.82 – 0.71), but not statistically significant, decrease in mortality in Medicare enrollees residing in the counties with a decrease in MWh of coal generation.

Table 5. Difference-in-Difference Coefficients and 95% Confidence Intervals

Analysis	Unadjusted[38]	Adjusted: Individual and Area Level Characteristics[39]	Adjusted: Individual and Area w/ Cluster[40]	Adjusted: Individual and Area Level + SO2/MWh[41]	Adjusted: Individual and Area + SO2/MWH w/ Cluster[42]
1[43]	0.0014 (-0.0017 , 0.0045)	0.0014 (-0.0017 , 0.0045)	0.0015 (-0.0015 , 0.0043)	-0.00053 (-0.0082 , 0.0072)	-0.00053 (-0.0082 , 0.0072)
p-Value	0.37	0.36	0.33	0.89	0.89
2[44]	-0.00024 (-0.0032 , 0.0028)	-0.00029 (-0.0033 , 0.0027)	-0.00029 (-0.0041 , 0.0035)	-0.0018 (-0.0056 , 0.0020)	-0.0018 (-0.0066 , 0.0030)
p-Value	0.88	0.85	0.88	0.36	0.47
4[45]	0.0021 (-0.00073 , 0.0049)	0.0021 (-0.00071 , 0.0050)	0.0021 (-0.0011 , 0.0053)	N/A[46]	N/A
p-Value	0.15	0.14	0.20		

Analysis 2. Percent Decrease in MWh of Coal Electricity Generation

Analysis 2 maintains consistency with the nearly 90 county comparison groups in Analysis 1, while considering the relative change in MWh. The analysis compares the percent change in MWh of coal electricity generation between 90 counties with the largest percent MWh decrease in coal electricity generation (55.80 - 516.49% decrease in MWh) in 90 counties with no change or a small decrease (0 - 8.49% decrease) in MWh of coal electricity generation. The 180 counties in Analysis 2 represented 128,714 unique Medicare enrollees and 239,543 individual Medicare files in 2011 and 2012.

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38 Proportion Mortality for Medicare Enrollee x Residing in County y = β0+ β1 x Int1-3+ β2 x year+ β3 x Int1-3 x year

39 Proportion Mortality for Medicare Enrollee x Residing in County y = β0+ β1 x Int1-3+ β2 x year+ β3 x Int1-3 x year+Cov. Cov = age, sex, race, poverty, income, unless stated otherwise.

40 Proportion Mortality for Medicare Enrollee x Residing in County y = β0+ β1 x Int1-3+ β2 x year+ β3 x Int1-3 x year+Cov, Cluster (County). Cov = age, sex, race, poverty, income, unless stated otherwise.

41 Proportion Mortality for Medicare Enrollee x Residing in County y = β0+ β1 x Int1-3+ β2 x year+ β3 x Int1-3 x year+Cov. Cov = age, sex, and race, poverty, income, SO_2 / MWh unless stated otherwise.

42 Proportion Mortality for Medicare Enrollee x Residing in County y = β0+ β1 x Int1-3+ β2 x year+ β3 x Int1-3 x year+Cov, Cluster County.Cov = age, sex, and race, poverty, income, SO_2 / MWh unless stated otherwise.

43 Race and percent poverty not significant and excluded from model.

44 Percent poverty was not significant when median household income was added to the model therefore percent poverty was excluded from model.

45 Race not significant and excluded from model. Percent poverty was not significant when median household income was added to the model therefore percent poverty was excluded from model.

46 The absolute value of SO_2 emissions is not included in the model since it is used to define the treatment and control groups.

Table 5 presents the results of the adjusted and unadjusted difference-in-difference estimates for Analysis 2. A small decrease in mortality (-0.24%, 95% CI -0.32 - 0.28 to -0.029%, 95% CI -0.33 - 0.27) was found for the intervention group. The decrease in mortality varied in the adjusted and unadjusted models and was not statistically significant, the p-values for the interaction coefficient were between 0.85 – 0.88.

Analysis 3. Percent Change in SO_2 Emissions per MWh of Coal Generation

In Analysis 1, one of the largest predictors in the model was the absolute value of SO_2/MWh in a county. This suggests SO_2/MWh of coal electricity generation sources in a county could be a useful metric to predict changes in mortality in the Medicare cohort. Analysis 3 tests whether 90 counties with a large percent decrease in SO_2/MWh from 2011 to 2012 (-12 – -69,701% SO_2/MWh) observed a different mortality in Medicare enrollees compared 90 counties with a percent increase in SO_2/MWh (11 – 10,161% SO_2/MWh). The increase in SO_2/MWh was used in this analysis since there were only 337 counties with data for both 2011 and 2012. The 180 counties in Analysis 4 represented 148,285 unique Medicare enrollees and 276,230 individual Medicare files in 2011 and 2012.

Table 5 presents the results of the adjusted and unadjusted difference-in-difference estimates for Analysis 3. In Analysis 3, a small increase in mortality (0.21%, 95% CI -0.071 - 0.53) was found in the intervention group. Similar to Analysis 1 and 3, despite the large difference in the racial distribution in the summary statistics, race was not a statistically significant predictor in the model and was removed. The decrease in mortality was consistent in the adjusted and unadjusted models and was not statistically significant, the p-values for the interaction coefficient were between 0.14 – 0.20.

Sensitivity Analyses

NO_2 Emissions

Despite no statistically significant change in mortality found following a natural intervention that resulted in less electricity generation from coal power plants, a sensitivity analysis was conducted to test confounding from transportation emissions. NO_2 concentration was added to the models in Analysis 1-3 as an indicator of transportation emissions. In general, adding the county level average ppb of NO_2 to the model either had no effect on the difference-in-difference interaction or increased the coefficient for the interaction coefficient. Table 6 summarizes the findings of the sensitivity analysis. The interaction coefficients in Analysis 1-3 continued not to be statistically significant when adjusting for NO_2 concentration. When NO_2 was added to the model in Analyses 2, SO_2/MWh became insignificant and was dropped.

Table 6. Difference-in-Difference Coefficients and 95% Confidence Intervals with NO_2 Sensitivity Analysis

Analysis	Unadjusted	Adjusted			
		Individual Level Characteristics[47]	Individual w/ Cluster	Individual Level + SO2/MWh	Individual + SO2 w/ Cluster
1[48]	0.0014 (-0.0017 - 0.0045)	0.0014 (-0.0017 - 0.0045)	0.0014 (-0.0015 - 0.0043)	-0.00085 (-0.0086 - 0.0069)	-0.00085 (-0.0087 - 0.0069)
p-Value	0.37	0.38	0.35	0.83	0.83
NO_2			0.0014 (-0.0015 – 0.0043)		-0.00093 (-0.0087 – 0.0068)
2	-0.00024 (-0.0032 - 0.0028)	-0.00014 (-0.0031 - 0.0029)	-0.00014 (-0.0038 - 0.0036)	-0.0015 (-0.0053 - 0.0022)	-0.0015 (-0.0063 - 0.0033)
p-Value	0.88	0.93	0.94	0.42	0.53
NO_2			-.00011 (-0038 - .0036)		-0.0015 (-0.0063 – 0.0033)
3[49]	0.0021 (-0.00073 - 0.0049)	0.0037 (-0.00065 - 0.0050)	0.0022 (-0.0010 - 0.0054)	N/A[50]	N/A
p-Value	0.15	0.13	0.18		
NO_2			0.0022 (-0.0010 - 0.0054)		

MWh Association to Hyads

The MWh exposure metric was found to have a low correlation to Hyads using a Spearman test and a first difference regression. The results are presented in Table 7. SO_2 / MWh was also found to have a small correlation with Hyads.

Table 7. MWh Association to Hyads Sensitivity Analysis

	MWh (2012)	SO_2 / MWh (2012)
Hyads Spearman Correlation	0.15 (p-value, 0.0015)	0.17 (p-value, 0.0016)

47 Age, sex, and race unless stated otherwise.

48 Race not significant and excluded from model.

49 Race not significant and excluded from model.

50 The absolute value of SO_2 emissions is not included in the model since it is used to define the treatment and control groups.

Discussion

This study found that there is no statistically significant association between three energy indicators, 1.) MWh of coal-based electricity generation, 2.) the percent change in MWh of coal generation, and 3.) SO_2 emissions per MWh of coal generation, and mortality in the Medicare cohort between 2011 and 2012. This finding could be due to at least five factors.

1) *MWhs of Coal Generation is not an Accurate Predictor of Exposure*
   One, MWhs of coal generation is not an accurate predictor of exposure to the types of air pollution that are associated with premature mortality. Several publications have found an association between switching to low carbon fuels and decreases in premature mortality. Studies have even monetized the benefits as discussed in Chapter 3 (e.g., Bounocore, 2014; Penn, 2017). Additional studies that have been conducted to test the association between specific types of pollution from coal power plants and adult mortality have also observed an association. For example, Strasert. Teh, and Cohan used photochemical modeling to project the changes in $PM_{2.5}$ and ozone and associated health impacts from the closure of 13 coal-fired power plants in Texas and found a decrease of up to 0.9 ug/m^3 of $PM_{2.5}$ and 3.3 ppb of ozone (Straset, 2019). It is possible that MWh of coal generation is simply not an accurate predictor of $PM_{2.5}$ and ozone concentrations. The fact that only a small association was found between the exposure metric for MWh and SO_2 / MWh and Henneman and Hyads (Spearman correlation of 0.15 – 0.17) further reinforces the conclusion that MWh is not an adequate indicator of exposure for air pollution from coal power-plants that has been found to be associated to premature mortality, e.g., $PM_{2.5}$. It is also possible that MWhs of coal generation is not an accurate predictor of exposure when aggregated at the county level since there was likely unmeasured confounding and effect modification in the county level health outcome data (mortality increased from 2011 - 2012 in Analysis 1 - 3). Further analysis could be conducted to test the association between a change in MWh at the power-plant level and health outcomes at the zipcode or census tract level.

2) *Low Association between Coal-fired Power Plant Exposure and Adult Morality*
   Two, the association between coal-fired power plant exposure and adult morality could be low. Several studies have found an association between a transition to cleaner electricity fuels and decreases in premature mortality, including the monetized benefits of those decreases (Buonocore, 2014; Penn 2017). A summary is provided in Chapter 3. Several of the studies reviewed in this chapter have found an association between decreases in power plant emissions and coal power plant retirements and acute health outcomes (HEI, 2016; Li, 2014; Henneman, 2019; Amster, 2019; Peterson, 2020; Casey, 2018). Most recently Henneman conducted a DID analysis on the Medicare cohort using methods to quantify source apportionment from power plants. Similar to this research, Henneman also found a

very low association between coal-fired power plant exposure and all-cause mortality. Although a strong association was found for other cardiovascular diseases (Henneman, 2019). However, only one publication identified a statistically significant association between power plant emissions and premature adult mortality (Straset, 2019). Therefore, part of the rationale for the lack of an association between MWh and mortality in the Medicare cohort could be the lack of power in the study to identify an association.

Another reason for the low association found could be the short timeframe between the change in exposure and the measured health outcome. One year could be an insufficient timeframe to observe a measurable effect in morality. Some DID studies have included a "wash out" period following the exposure. Despite the fact that previous literature has found an association between short-term exposure to air pollution and mortality, future analyses could include a few year washout period.

Finally, the lack of source apportionment modeling in this study could be another reason that a low association was found. As described in Chapter 3, proximity to a power plan, including whether the Medicare enrollee resides in a county upwind or downwind of a power plant could impact the health outcome. Additional analyses should consider taking into account source apportionment.

3) *Unknown Factor Resulting in Increase in Mortality in Medicare Cohort*
   Three, there is another factor leading to an increase in mortality that is not captured in the model. Mortality increased between 1.5 - 6.5% from 2011 to 2012 in both the intervention and control groups. Potentially because in most groups the average age of the Medicare enrollee also increased by at least one year between 2011 and 2012, therefore the 2012 Medicare cohort was older. There could also be an additional factor that is not accounted for in the model that resulted in an increase in mortality.

4) *Exposure Variable Standard Errors to Large*
   Four, the level of association in the exposure variables was not significantly different between the intervention and control group. The standard errors of the exposure metrics in this analysis were very large and often overlapped between the treatment and control groups. The large standard errors could have reduced ability of the model to measure an association. In addition, the tons of SO_2 emission per MWh in each county increased from 2011 to 2012, which is unexpected. In some cases the increase in SO_2 emissions / MWh was larger in the intervention group than the control group. One might have guessed that the dirtier coal plants retired or retrofitted first to comply with MATS. Future studies could conduct additional statistical analysis to adjust for underlying trends that change annually in the control and intervention groups and expand the timeframe of the analysis to include multiple years.

5. *Multicollinearity*
   Five, there could have been a large amount of multicollinearity in the adjusted models in this analysis due to the addition of SO_2/MWh. For example, when SO_2/MWh was added to the model in Analysis 1, the sign of the DID interaction coefficient switched from positive to negative. Since the treatment and control groups were defined using MWh, future analysis should exclude MWh from the variables in the model.

Racial Distribution

The racial distribution of the intervention and treatment groups varied widely depending on the analysis. In Analysis 1, the intervention group was more diverse. In Analysis 2 there was no difference. In Analysis 3, the control group had a higher proportion on Black and Hispanic Medicare enrollees than the intervention group. Despite this finding, race was not a significant variable in the models for three out of four of the analyses.

Study Weaknesses

This study design has several weaknesses in addition to the five described above. Many lifestyle and environmental changes can affect mortality. Limiting the analysis to the types of mortality that have been found to have the strongest association with exposure to power plant emissions could increase the likelihood of statistically significant results, as was found in a recent study on coal power plants and mortality in the Medicare cohort (Henneman, 2019). In this research, data was only available for three potential individual level and two area level confounding variables, all of which were tested in each model. Although a DID approach was used to account for differences within each group, there could be annual changes that are not picked up in the DID model.

This study is the first national analysis of the association between MWh of coal generation and mortality in the Medicare cohort. Several studies have found an association between proximity to coal power plant retirements and decreases in adverse health outcomes using the DID approach without estimating the change in air pollution concentration (Casey 2018a, Casey 2018b, Casey 2020). These studies were conducted using significantly smaller study populations over one or two states. Part of the rationale for a lack of association in this study could be due to the large size of the intervention and control groups, which could wash out potential associations due to the use of binary instead of continuous variables at the individual level.

Although this research does not evaluate the causes for the decrease in high carbon electricity generation, it is worth mentioning that a proportion of the decrease was due to improvements in energy efficiency in buildings, industry, and households (EIA, 2020).

This research tested the ability to utilize an easy to understand energy metric to make generalizations about the health effects of policy interventions without conducting a full analysis of the direct association between energy policy to emissions to health outcomes. If a statistically significant association was found in this paper, it would have had a far-reaching effect on policy making and was therefore a worthwhile aim for study. As discussed above, additional research could be conducted to refine the model and compare the correlation of the exposure measures tested to $PM_{2.5}$ and ozone. A study of the association of MWh with cardiovascular mortality with a longer study period and utilizing source apportionment data would be worthwhile.

Chapter 5. Conclusion

Several components of this dissertation resulted in innovative findings. This research is the first analysis to 1.) document the role that environmental health played in the advancement of climate change policy in the Obama Administration, and, 2.) identify new environmental health literature needed to create more durable environmental regulations. The findings in Chapter 2 will inform new environmental health research, which in turn could support the development of regulations with stronger scientific, economic, and legal grounding. Chapter 3 contains the first literature review of models and methods to monetize the health benefits of shifting to low carbon fuels for electricity generation in the U.S. and identifies the strongest model predictors. A better understanding of the model predictors in econometric analyses of the health benefits of modifications in electricity fuels will help inform new econometric models and epidemiology studies. Chapter 4 is the first national epidemiology study to evaluate the direct association between a decrease in the MWh of high carbon electricity fuels from 2011-2012 and mortality in the Medicare cohort.

Each chapter contains novel findings that helped inform the research in the other chapters and add new knowledge to the environmental health field. The major findings include:

Chapter 2 found that environmental health literature helped to provide the legal foundation for regulating greenhouse gases through the Clean Air Act. In addition, the findings also reinforced that it is imperative to continue to develop new environmental health literature and monitoring data on the health impacts of climate change in the United States in order to develop effective U.S policy.

Chapter 2 also found that environmental health literature provided the information necessary to build the economic case for EPA to promulgate greenhouse gas standards. Four of the eleven Obama-Biden major climate change rulemakings would not have been cost-effective without monetizing the health, environmental, and societal benefits. The seven rulemakings that remained cost-effective were due to savings in fuel (EPA rules for cars and trucks) or energy savings (DOE energy conservation standards). The analysis also found that 9-100 percent of the benefits in major climate change rulemakings promulgated in the Obama Administration were due to health-related benefits. In three out of eleven climate change rulemakings, 100 percent of the monetized benefits are health-related.

Chapter 3 reviewed the current methodologies to measure the monetized health benefits of modifications in electricity fuels in the U.S. across various spatial and temporal parameters, compared their findings, and evaluated the variables that are the strongest predictors within each methodology. A thorough review of the literature found that the range of monetized benefits for shifting to solar energy is 1-2.7 cents/kWh and wind energy is 1.3-9 cents/kWh in the United States. Renewable portfolio standards lead to benefits of 3.7-8 cents/kWh. Conversely, the monetized health impact of fossil fuels ranges from 0.1-32 cents/kWh in the United States. The review also found that the pollutant emitted, temperature, the power plant location, the type of fuel deployed or offset, and type of the health benefits model utilized were the largest predictors of the monetized health benefits.

Chapter 4 is the first national epidemiology study examining the direct association between phasing out the generation of traditional high carbon fossil-based electricity and the effect on mortality. The study evaluated a decrease in four indicator variables for MWh of electricity generation from coal power plants in 492 counties from 2011 to 2012, during one of the largest shifts to low carbon electricity fuels in history. Using a difference-in-difference (DID) approach, no statistically significant change in mortality in Medicare enrollees was found when comparing the three intervention groups to the control groups and adjusting for confounding. The three indicator variables analyzed yielded the following results. The difference between annual mortality in 90 counties that observed a large decrease in MWh and SO_2 adjusted MWh between 2011 and 2012 and 90 counties that observed small decrease or no change in the corresponding exposure metric was less than one percent (Analysis 1, $\beta = 0.14\%$, 95% CI -0.17 - 0.45, Analysis 2, $\beta = -0.024\%$ 95% CI -0.32 - 0.28; (Analysis 3, $\beta = -0.21\%$ 95% CI -0.073 - 0.49). This research provides further evidence supporting the need to conduct multi-step analyses to determine the health effects of energy policy interventions.

In conclusion, this dissertation contributed several important findings to the environmental health field including, identifying new environmental health literature that could increase the durability environmental regulations, providing rationale for more federal funding for environmental health literature, identifying the variables policy makers should focus on to determine the location of renewable energy projects, and providing new evidence that untested energy indicator variables should not be used to estimate health effects of energy policy interventions. Although each Chapter had its own weaknesses, which are described in detail, in whole, this dissertation makes a meaningful contribution to the field of environmental health science.

Appendix A. Counties included in Analysis 1-3 of Epidemiology Study

Analysis 1 Counties				Analysis 2 Counties			
Intervention		Control		Intervention		Control	
COUNTY	STATE	COUNTY	STATE	county	state	county	state
county	state	county	state	Prowers	CO	Duplin	NC
Mason	WV	Clay	IA	Marion	IA	Richland	SC
Fort Bend	TX	Woodford	KY	Berks	PA	Bernalillo	NM
Harrison	WV	Saline	MO	Darlington	SC	St Charles	MO
Coshocton	OH	Kershaw	SC	Anderson	SC	Black Hawk	IA
Washington	OH	Dubois	IN	Aiken	SC	Washington	MN
Boone	KY	Orange	NC	Effingham	GA	Henderson	KY
Monroe	MI	Lincoln	WI	Olmsted	MN	Putnam	IL
Catawba	NC	Dane	WI	Johnson	IA	Trimble	KY
Grimes	TX	Blair	PA	Kern	CA	Belmont	OH
Lake	OH	Miami	IN	Wood	WI	Isle of Wight	VA
Lawrence	KY	Morton	ND	Preston	WV	Traill	ND
St Louis	MO	Manitowoc	WI	Lake	IN	Citrus	FL
Bristol	MA	Columbus	NC	Yates	NY	Harrison	TX
Hawkins	TN	Mower	MN	Saline	MO	Grant	WV
Harrison	MS	Washington	MD	Clark	KY	De Soto	LA
Marathon	WI	Bernalillo	NM	Chatham	NC	Atascosa	TX
Jasper	IN	East Baton Rouge	LA	Mower	MN	Mercer	KY
Bartow	GA	Cumberland	ME	Cherokee	KS	Montrose	CO
Jefferson	IN	Hampden	MA	Tompkins	NY	Allegheny	PA
Greene	PA	Choctaw	AL	Lawrence	KY	Buffalo	WI
Lewis	WA	Worcester	MA	Chautauqua	NY	Uintah	UT
Cobb	GA	St Jospeh	IN	Portage	WI	Beaver	PA
Anne Arundel	MD	Somerset	MD	Robeson	NC	Independence	AR
Will	IL	Portage	WI	Dubuque	IA	Beauregard	LA
Shelby	AL	Beauregard	LA	Bedford	VA	Miami	IN
Limestone	TX	Traill	ND	Hawkins	TN	Wilbarger	TX
Coconino	AZ	Alger	MI	Clay	MO	Jackson	MO
Coweta	GA	Duplin	NC	Orange	NY	Lowndes	MS
Montour	PA	Leflore	MS	Delaware	PA	Schuylkill	PA
Putnam	GA	Johnson	IA	Essex	MA	Hartford	CT
Millard	UT	Tuscarawas	OH	Vigo	IN	Auglaize	OH
Mayes	OK	Champaign	IL	Hudson	NJ	Winnebago	WI
Muskogee	OK	Bedford	VA	Wilcox	AL	Larimer	CO
Dearborn	IN	Oxford	ME	Fluvanna	VA	Dodge	NE
Massac	IL	Marion	WV	Washington	OH	Carbon	UT
Woodbury	IA	Luzerne	PA	Mercer	NJ	Carroll	KY
Pottawatomie	KS	Winnebago	WI	Scotts Bluff	NE	Williamson	IL

Heard	GA	Florence	SC	East Baton Rouge	LA	Hampden	MA
Prince Georges	MD	Richland	OH	Richland	OH	Freestone	TX
Fayette	TX	Onondaga	NY	Pickaway	OH	Jasper	MO
Chesapeake	VA	Schuylkill	PA	Ashland	WI	Elk	PA
Colbert	AL	Wilcox	AL	Morgan	IL	Somerset	MD
Greene	MO	Oneida	WI	Fairfield	CT	Berkeley	SC
Washington	AL	Belmont	OH	Northampton	PA	Contra Costa	CA
Lucas	OH	New Castle	DE	Manitowoc	WI	Warrick	IN
Escambia	FL	Douglas	IL	Gaston	NC	Erie	PA
Noble	OK	Montgomery	IN	McMinn	TN	Pike	IN
St Clair	MI	Davidson	TN	Rowan	NC	UTAH	UT
Apache	AZ	Fairbanks North Star	AK	Richmond	GA	Rapides	LA
Vigo	IN	Adams	IN	Trumbull	OH	Renville	MN
Randolph	MO	Isle of Wight	VA	Delta	MI	San Juan	NM
Bexar	TX	Price	WI	Imperial	CA	Des Moines	IA
Duval	FL	Washington	LA	Southampton	VA	Rosebud	MT
Niagara	NY	Haywood	NC	Leflore	MS	Luzerne	PA
Franklin	MO	Black Hawk	IA	Pike	IL	Cumberland	NJ
Humphreys	TN	Miami	OH	Menominee	MI	Sullivan	TN
Pointe Coupee	LA	Crow Wing	MN	Cuyahoga	OH	Pottawattamie	IA
Lake	IN	Cumberland	NJ	Dane	WI	Covington	VA
Sullivan	IN	Jasper	MO	Cobb	GA	Converse	WY
Gallia	OH	Little River	AR	Dougherty	GA	Halifax	NC
Cleveland	NC	Maui	HI	Etowah	AL	Apache	AZ
York	PA	Boulder	CO	Clay	IA	Little River	AR
Marshall	WV	Polk	IA	City of Richmond	VA	Salt Lake	UT
Randolph	IL	Dodge	WI	Wayne	IN	Washington	LA
Orange	FL	Renville	MN	Snyder	PA	Jefferson	MO
Platte	WY	Imperial	CA	Dodge	WI	Boulder	CO
Jefferson	KY	Talladega	AL	Woodford	KY	Columbus	NC
Rusk	TX	Auglaize	OH	Montgomery	IN	Lincoln	NE
Armstrong	PA	Monroe	IA	San Bernardino	CA	Miami	OH
Hudson	NJ	Contra Costa	CA	Hardin	TN	Monroe	GA
Adams	OH	Montgomery	OH	Hennepin	MN	Grant	WI
Gaston	NC	Hancock	ME	Laurens	GA	El Paso	CO
San Juan	NM	Lowndes	MS	Jackson	FL	New Castle	DE
Putnam	WV	Dodge	NE	Morgan	IN	Martin	NC
Jefferson	OH	Outagamie	WI	Horry	SC	Adams	IN
Milwaukee	WI	Alpena	MI	Floyd	IN	Lincoln	WY
Rogers	OK	Montgomery	VA	Benton	MN	Hancock	KY
Cook	IL	Hartford	CT	Rockingham	NH	Fairbanks North Star	AK
Jasper	IL	Covington	VA	Edgecombe	NC	Lamb	TX

Chesterfield	VA	Twin Falls	ID	Marshall	IA	Itasca	MN
Titus	TX	Elk	PA	Pembina	ND	Navajo	AZ
Chautauqua	NY	Blue Earth	MN	Lucas	OH	Coconino	AZ
Walker	AL	Menominee	MI	Ashtabula	OH	Onondaga	NY
Georgetown	SC	Hardin	TN	Blue Earth	MN	Mason	IL
Stokes	NC	Hennepin	MN	Rockingham	NC	Leflore	OK
Monroe	GA	UTAH	UT	Pima	AZ	Pleasants	WV
Tazewell	IL	Marion	IA	Scioto	OH	Colfax	NM
Floyd	GA	Martin	NC	Putnam	GA	Morton	ND
Jefferson	AL	Colfax	NM	San Joaquin	CA	Wayne	MI
Sherburne	MN	Erie	PA				
Charles	MD						
Clermont	OH						

Analysis 3 Counties

Intervention	Control		
county	state	county	state
Pulaski	KY	Vermillion	IN
Dougherty	GA	Pike	IN
Person	NC	Hampden	MA
Bristol	MA	Fairfield	CT
Black Hawk	IA	New Hanover	NC
Sussex	DE	Brunswick	NC
Tompkins	NY	Washington	PA
Clearfield	PA	Russell	VA
Sangamon	IL	Cleveland	NC
Grant	WI	Mason	WV
Spencer	IN	Webster	KY
Rockingham	NC	Halifax	VA
Converse	WY	Larimer	CO
Escambia	FL	York	PA
Humphreys	TN	Catawba	NC
Fayette	TX	Boone	KY
Sherburne	MN	De Soto	LA
Pickaway	OH	Jefferson	AR
Aiken	SC	Carroll	KY
Greene	MO	Mercer	KY
Henderson	KY	San Juan	NM
Hudson	NJ	Orange	FL
Douglas	NE	Montrose	CO
Jefferson	MO	Warrick	IN
St Louis	MO	Mecklenburg	VA
Titus	TX	Big Horn	MT

Bexar	TX	Wayne	NC
Mobile	AL	Des Moines	IA
Otter Tail	MN	Independence	AR
Rusk	TX	Grant	WV
Orange	NY	McCracken	KY
Boone	MO	Choctaw	MS
Allegany	MD	Eureka	NV
Vernon	WI	Citrus	FL
Milwaukee	WI	Freestone	TX
Roane	TN	Uintah	UT
Jefferson	OH	Will	IL
Allegheny	PA	Alexandria	VA
Putnam	WV	Trimble	KY
Henry	MO	Pueblo	CO
Oliver	ND	Pointe Coupee	LA
Buchanan	MO	Lewis	WA
Linn	IA	Chatham	GA
Clay	IA	Denver	CO
Duval	FL	Stokes	NC
Hamilton	OH	Marion	IN
Chautauqua	NY	Mississippi	AR
Mercer	ND	Calcasieu	LA
Lincoln	WY	Lawrence	PA
St Charles	MO	Jefferson	KY
Merrimack	NH	Coconino	AZ
Muhlenberg	KY	Allamakee	IA
Chesterfield	VA	Heard	GA
Millard	UT	King George	VA
Walker	AL	Gibson	IN
Dubuque	IA	Mayes	OK
Brown	WI	Atascosa	TX
Apache	AZ	Posey	IN
Cochise	AZ	Grant	SD
Shelby	AL	Etowah	AL
Rapides	LA	Montgomery	IL
Randolph	IL	Clinton	IA
Clermont	OH	Platte	MO
Adams	CO	Rogers	OK
Monongalia	WV	Martin	FL
Manistee	MI	Stewart	TN
Ashtabula	OH	Colleton	SC
St Louis	MN	Washington	MN
Richland	MT	Christian	IL
Goliad	TX	Tazewell	IL
Greene	PA	Jackson	AL

Lexington	SC	Eaton	MI
Muscatine	IA	Morgan	IN
Massac	IL	Putnam	FL
Berkeley	SC	Wilbarger	TX
Effingham	GA	Edgecombe	NC
Daviess	KY	Scott	MO
Harrison	TX	Orangeburg	SC
Sullivan	IN	Itasca	MN
Cape May	NJ	Scott	IA
Grimes	TX	Morrow	OR
Ohio	KY	Sumner	TN
Adams	NE	Anne Arundel	MD
Lake	IL	Southampton	VA
Williamson	IL	Cook	IL
Buncombe	NC	Dearborn	IN
Mason	IL	Jasper	IL
Huron	MI	Humboldt	NV
Gallia	OH	Hancock	KY
Franklin	MO	Ingham	MI

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