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Assessing the Air Quality and Health Impacts of Decarbonization Strategies in Connecticut

By

Danni Dong
Master of Science in Public Health

Department: Environmental Health-Epidemiology

Noah Scovronick, PhD
Committee Chair

Dan Loughlin, PhD
Committee Member

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Danni Dong

B.S.
University of Connecticut
2018

Thesis Committee Chair: Noah Scovronick, PhD

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a thesis submitted to the Faculty of the
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in partial fulfillment of the requirements for the degree of
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Abstract

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Background: Decarbonization strategies have emerged as crucial measures for mitigating climate change and enhancing air quality. Moreover, decarbonization is anticipated to yield significant health co-benefits, such as reduced respiratory and cardiovascular disease among vulnerable populations. Connecticut faces particularly poor air quality, with all eight counties currently in nonattainment of the National Ambient Air Quality Standard.

Methods: This study examines the impact of decarbonization on air quality, health outcomes, and environmental justice in Connecticut using modeling tools developed by the U.S. EPA. Two scenarios (DC1 and DC2) were modeled until 2050 in GCAM, incorporating a combination of state and federal legislation and targets, and generating county-wise emissions data for key pollutants (NO_x, SO_2, VOC, NH_3, and PM2.5). These emissions were input into COBRA to estimate PM2.5 concentrations and health benefits. Finally, EJScreen data was utilized to assess correlations between demographic indicators and projected mortality costs.

Results: Decarbonization scenario DC1, which includes regional CO_2 caps, California Light-Duty vehicle electrification targets, and the Medium and Heavy-Duty Electrification Memorandum of Understanding, is expected to yield $80.7 million (2017$) in health benefits for Connecticut annually. DC2, which employs the same targets but limits biomass and carbon capture and storage (CCS) usage, yields $99.4 million in health benefits annually. The association between health benefits and decarbonization appears particularly strong among minority populations, with a correlation coefficient exceeding -0.87 for DC2.

Conclusion: The findings indicate that more ambitious decarbonization targets could yield substantial health benefits for Connecticut residents. Further research is required to analyze regional emission contributions to Connecticut's overall air quality.

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INTRODUCTION

Background

Climate change, one of the most pressing challenges of our time, poses significant threats to human health and economic stability worldwide (United Nations, 2021). As global temperatures continue to rise, a growing consensus among scientists and policymakers emphasizes the urgent need for comprehensive decarbonization efforts (Rogelj et al., 2018). Decarbonization is the process of reducing carbon dioxide emissions from energy consumption and industrial processes. It is a crucial component in the global effort to limit global warming to well below 2°C, as outlined in the Paris Agreement (UNFCCC, 2015). By transitioning to cleaner energy sources and enhancing energy efficiency, we can significantly reduce the concentration of greenhouse gasses in the atmosphere.

In the past decade, there has been a significant increase in decarbonization efforts within the US (EIA, 2021). The Energy Act of 2020 allocated billions of dollars to support the development of renewable energy, energy storage, advanced nuclear, and carbon capture technologies (U.S. Department of Energy, 2022). The Infrastructure Investment and Jobs Act of 2021 was a $1.2 trillion bipartisan infrastructure bill that included approximately $550 billion in new spending on clean energy research, public transit improvements, and water infrastructure upgrades (The White House, 2021).

In 2022, the Inflation Reduction Act (IRA) was passed, marking the most ambitious energy security and climate change mitigation law ever passed (The White House, 2022). The $370 million bill, which aims to decarbonize every sector of the economy, provides tax credits and grant funding for states and electric utilities to transition to renewable electricity. The bill also offers tax credits for electric vehicles that are produced domestically and funding to upgrade the fleets of governmental agencies (The White House, 2022)

While decarbonization is the goal of these laws, efforts need to be made to quantify the carbon reductions as well as the additional impacts on people from these policies, both now and into the future. This information can help decision makers prioritize actions across sectors, pollutants, and time, with the objective of maximizing benefits. For example, decarbonization also can play a vital role in enhancing public health and decreasing the burden of disease. In addition to carbon dioxide, fossil fuel combustion releases harmful air pollutants, such as particulate matter (PM), nitrogen oxides (NOx), ammonia (NH3), volatile organic compounds (VOCs), and sulfur dioxide (SO2). These pollutant species are the precursors to PM2.5, which are small particles that can penetrate into the lung's alveolar sacs, enter the bloodstream, and cause disease (WHO, 2023).

The Link Between Air Pollution and Health

Air pollution has been consistently linked to respiratory diseases, such as asthma, chronic obstructive pulmonary disease (COPD), and respiratory infections (Dominski et al., 2021). Investigation into the long-term effects of air pollution on lung function in children found that exposure to nitrogen dioxide and PM resulted in decreased lung function growth in children ages 10 to 18 (Gauderman et al., 2004).

Another cross-sectional study that examined the association between outdoor air pollution and allergies in Taiwanese schoolchildren discovered that exposure to SO_2, CO, and NO_x increased the risk of allergic rhinitis (Hwang et al., 2006). A large-scale epidemiological study in 2015 involving 652 cities worldwide estimated that the global burden of premature deaths from PM was 4.2 million (Cohen et al., 2017).

The most ubiquitous exposure to PM in the United States comes from traffic emissions (CA Air Resources Board, 2023). Using data from the Framingham Heart Study, researchers found that exposure to traffic emissions and PM was associated with decreased lung function, especially those with pre-existing respiratory conditions. The authors concluded that reducing exposure to air pollution could help improve lung function associated in growing adolescents (Rice et al., 2016).

Cardiovascular diseases have also been closely linked to air pollution (Rajagopalan et al., 2018). Research collaborators working with the American Heart Association concluded that even short-term exposure to high levels of PM could trigger acute cardiovascular events (Brook et al., 2010). Long-term exposure to air pollution has also been associated with increased mortality rates. Danish researchers estimated that approximately 15% of deaths from cardiovascular disease in their cohort could have been attributed to exposure to PM, NO_x, and ozone (O_3) (Hvidtfeldt et al., 2019).

There is evidence that women may be disproportionately impacted by air pollution. Researchers who studied the association between long-term exposure and the incidence of cardiovascular events in a cohort of women found a 76% increase in the risk of cardiovascular events for every 10 μg/m^3 increase in fine particulate air pollution (Miller et al., 2007). The same decrease in PM was associated with a 6% decrease in cardiovascular mortality among women (Laden et al., 2006).

Numerous studies have highlighted the link between race, income, and the impact of air pollution (Liu et al., 2021) For example, one study found that non-white populations in the United States experienced 38% higher levels of nitrogen dioxide (NO_2) exposure compared to white populations, with disparities being most pronounced in urban areas (Clark et al., 2014). Additionally, the authors estimated that reducing these disparities could prevent up to 7,000 deaths from heart disease annually among non-white populations. Another research group concluded that the inequitable distribution of environmental burdens is a result of systemic factors such as housing segregation, industrial land use, and limited political power, which hinder marginalized groups from advocating for cleaner environments and improved living conditions (Bullard, 2005). In essence, these findings reveal that the burden of air pollution is unjustly borne by vulnerable populations, perpetuating cycles of environmental injustice and social inequity.

Air pollution poses a significant burden on healthcare systems and the cost of healthcare. In a study of Ontario Canada residents, researchers found a strong correlation between PM and NO_x emissions and increased outpatient visits (To et al., 2015). A study in the US employing fine-scale modeling determined that air pollution contributed to over $88 billion in healthcare costs each year, and that strategically targeted mitigation efforts could decrease these costs by more than 50% (Goodkind et al., 2019). They proposed that targeted interventions, rather than large sweeping federal mandates, may provide more significant economic and public health advantages. Another study in the US estimated the cost of air pollution on the US economy to be over $131 billion each year, accounting for both lost productivity and healthcare costs. The authors mentioned the greatest improvements in air quality and associated costs are expected when focusing on transportation and industry (Muller et al., 2011).

Decarbonization Methods

Traditional decarbonization methods include reducing carbon from combustion emissions using carbon capture and storage (CCS) and transitioning away from fossil fuels to renewables (Intergovernmental Panel on Climate Change, 2015). One such technique is carbon capture and storage (CCS), which takes carbon produced from industrial plants and buries it underground. CCS has been touted as a potential avenue for reducing carbon emissions without disrupting current fossil fuel-based electricity generation facilities.

While carbon capture has some potential promise for mitigation, it has its own risks. There is an energy penalty associated with CCS, as it requires burning more fuel to capture the carbon. Additionally, pipeline infrastructure is often needed to transport the captured CO2, which can be expensive and difficult to site. CCS can quickly become costly and complicated when questions arise regarding who will build, own, and operate the plant. In several studies that evaluate the costs and benefits of CCS, researchers argue that CCS is still relatively unproven and that there are numerous technical and economic obstacles associated with its large-scale implementation (Budinis et al., 2018). Compared to other mitigation options, such as wind and solar power, CCS may even result in increases in the emissions of some pollutants, including PM2.5 (Ou et al., 2018). Consequently, communities that may have seen health benefits from the transition to renewable energy may continue to face respiratory and cardiovascular health concerns from poor air quality, and the introduction of new CCS capacity may exacerbate the problems.

Biomass has also been discussed as a promising method to decrease carbon emissions in the power sector. Biomass is a renewable energy source derived from organic materials, including plant and animal residues, agricultural and forestry waste, and energy crops (EIA, 2022). As an alternative to fossil fuels, biomass energy may reduce greenhouse gas emissions. Biomass, typically in the form of plant material, absorbs CO2 from the atmosphere through photosynthesis. Subsequently, when this biomass is combusted for energy production, the previously sequestered CO2 is released back into the atmosphere. This cyclical process of CO2 absorption and emission results in a net-zero carbon footprint for biomass, rendering it a carbon-neutral fuel source.

Furthermore, when bioenergy is combined with CCS (BECCS), it can achieve a negative CO2 signature, as some of the emitted CO2 is captured and stored, preventing its release into the atmosphere. However, there are notable drawbacks to biomass energy (Freiberg et al., 2018). Unsustainable biomass production can lead to deforestation and a decline in biodiversity. Additionally, in a paper discussing biomass carbon neutrality, one author contends that biomass can only be considered carbon neutral if it is sustainably produced and accounts for the carbon emissions generated during production and transportation (Rhodes & Keith, 2008). The efficiency of biomass conversion technologies is generally lower than that of fossil fuel-based systems, which may require larger land areas for biomass cultivation to meet energy demands (Henry, 2010). Put together, biomass aids in decarbonization, but could exacerbate the PM problem.

Given these barriers, and the lack of a strong regulatory driver to date, there has been limited adoption of biomass for electricity production and no commercial applications of CCS in most of the U.S., and, in some areas, the prospects for adoption of these technologies in the coming decades is limited. For example, the high costs, policy and regulatory barriers, and public perception have pushed states in the Northeast to focus on more established renewable projects such as wind and solar, and this will likely continue into the future.

Health Co-Benefits of Decarbonization

Decarbonization co-benefits refer to the positive outcomes that result from implementing decarbonization strategies which extend beyond the primary goal of reducing greenhouse gas emissions (Haines et al., 2009). Previous studies have explored the health co-benefits of decarbonization, including the analysis of the Multi-State Medium and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding (MDHD EV MOU). The authors found that the lifetime health benefits of the MOU is between $690 and $3,300 per person (Funke, 2023). Researchers at the University of North Carolina also investigated the health co-benefits of greenhouse gas reduction actions, reporting that by 2050, greenhouse gas reductions would prevent approximately 1.3 million deaths (West et al., 2013).

Another study assessed the potential health co-benefits of the Paris Agreement and found that the mitigation cost ratio ranged between 1.45 and 2.19, indicating that the health benefits greatly exceeded the cost of decarbonizing (Sampedro et al., 2020). Additionally, Wei Peng's group conducted an analysis of Pennsylvania joining the Regional Greenhouse Gas Initiative (RGGI), and estimated cumulative monetized health co-benefits to be 17.7 to 40.8 billion USD (Yang et al., 2021).

Impacts on Connecticut

Air pollution in Connecticut is a significant public health concern, particularly in counties with high urban density such as Hartford and New Haven. According to the Connecticut Department of Energy and Environmental Protection (DEEP), the state has a number of sources of air pollution, including transportation, industry, and residential sources such as wood stoves and fireplaces (CT DEEP, 2023).

PM air pollution is a particular problem in Connecticut, with the state frequently receiving failing grades for PM pollution from the American Lung Association (ALA, 2021). In 2017, an estimated 783 deaths were attributed to exposure to PM2.5 (Cohen et al., 2017). Connecticut also experiences high levels of ozone (O3), and all eight counties are designated as being in nonattainment of the O3 National Ambient Air Quality Standard (CT DEEP, 2022a).

In response to the public health concerns related to air pollution, Connecticut has implemented several policies and programs to reduce emissions and improve air quality. These include the Connecticut Renewable Portfolio Standard, which requires a minimum percentage of electricity sold in the state to come from renewable sources, and the Connecticut Hydrogen and Electric Automobile Purchase Rebate Program, which provides financial incentives for the purchase or lease of electric and hydrogen fuel cell vehicles (CT DEEP, 2022b)

An important aspect of Connecticut’s air quality challenges is that the state’s air quality is significantly impacted by the emissions from states surrounding it, due to the prevailing wind patterns and the interconnected nature of the regional airshed. The northeastern United States is characterized by a high population density and heavily trafficked interstates including I-91, I-84, and I-281 (Hearst Connecticut Media Group, 2023). Furthermore, emissions originating from New York City, particularly the port and shipping activities, have a significant impact on Connecticut's air quality due to their upwind location (Port Authority NY NJ, 2023). These factors contribute to the generation of air pollution that can easily spread across state borders into Connecticut (CT DEEP, 2019a). One study found that 90% of Connecticut deaths are caused by PM2.5 pollution from electric power generation outside the state border (Thind et al., 2019).

As such, emissions from New York, New Jersey, Massachusetts, and Rhode Island, have been found to contribute to the air pollution experienced in Connecticut (Karagulian et al., 2015). This phenomenon is commonly referred to as "transported pollution" or "interstate pollution transport." The United States EPA recognizes the issue of transported pollution and has implemented policies to address it, such as the Clean Air Interstate Rule (CAIR) and the Cross-State Air Pollution Rule (CSAPR) (US EPA, 2016b). In 2023, the EPA also passed the Good Neighbor Plan, which aims to reduce ozone emissions from industrial facilities in 23 states. This new plan hopes to improve air quality in downwind states such as Connecticut (Kittrell, 2023).

Connecticut and its upwind states have recognized the potential co-benefits of decarbonization and states in the region have established ambitious targets to reduce GHG emissions. For instance, Connecticut enacted a statutory target in 2018 to reduce GHG emissions by 45% below 2001 levels by 2030 and 80% by 2050 (CT DEEP, 2019b). Similarly, neighboring states such as Massachusetts and New York have set their own ambitious goals; Massachusetts aims to reduce GHG emissions by 85% below 1990 levels by 2050 (CECP, 2022), while New York targets a reduction of 40% below 1990 levels by 2030 and at least 85% by 2050 (NYSERDA, 2022). To achieve these goals, regional initiatives such as the Regional Greenhouse Gas Initiative (RGGI) and the Medium and Heavy-Duty Electrification Memorandum of Understanding (MOU) have been implemented, promoting collaboration among states. The actions taken to meet these targets are expected to generate substantial co-benefits, such as improved air quality and health outcomes, which should be carefully considered when evaluating the overall impact of decarbonization policies (Perera et al., 2020).

RESEARCH OBJECTIVES

This thesis aims to build upon the existing studies that explore air quality co-benefits of decarbonization, while carving out a unique niche at the intersection of health, decarbonization policy, and environmental justice. Specifically, the study's focus is on Connecticut and the surrounding region, offering a localized perspective on an area that has historically dealt with poor air quality and nonattainment. While this work shares some similarities with the EV MOU analysis, it differs in its examination of broader regional decarbonization scenarios that encompass multiple sectors, including transportation, energy production, and industry. This approach provides a more comprehensive understanding of the potential health benefits and challenges associated with a multi-sector decarbonization strategy.

Similar to several other applications in the literature, this study uses results from the Global Change Assessment Model (GCAM) (Pacific Northwest National Laboratory, 1982) to explore various decarbonization scenarios. However, the study diverges from others with the inclusion of alternative scenarios that consider regional concerns about the viability of technologies related to biomass or carbon capture. Finally, this thesis examines county-level demographic information to draw inferences on the potential environmental justice impact decarbonization scenarios may have on communities. By incorporating these additional components, the results contribute to a more robust understanding of the potential health impacts and trade-offs associated with different decarbonization pathways in the context of CT and the surrounding region.

The specific objectives of the research presented in this thesis are to:

1. Analyze the current state of GHG emissions and air quality in CT, utilizing available data and relevant literature to establish a baseline for subsequent research and analysis;
2. Model the projected air quality in CT for the year 2050, under the assumption that the status quo is maintained;
3. Explore various policy scenarios that incorporate more stringent state-level GHG reduction targets, as well as limitations on decarbonization methods that may have adverse effects on air quality;

4. Assess the relationship between changes in air quality and associated health impacts, by examining total health benefits and disease incidence and identifying the sectors with the greatest influence on air quality and health outcomes; and,
5. Correlate co-benefits data with demographic information to identify vulnerable populations and counties in CT.

By accomplishing these objectives, this thesis will contribute to the understanding of the complex interplay between air quality, public health, and equity in Connecticut and the surrounding region, ultimately guiding decision-makers towards more effective strategies for mitigating air pollution. Furthermore, the results are intended to inform the development of targeted interventions to mitigate the negative effects of poor air quality on susceptible communities.

METHODS

This study leverages several EPA modeling tools that have been developed to inform policy decisions related to air quality and climate change: GLIMPSE (Global Change Assessment Model Long-term Interactive Multi-Pollutant Scenario Evaluator) (US EPA, 2015c), COBRA (Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool) (US EPA, 2020), and EJScreen (Environmental Justice Screening and Mapping Tool) (US EPA, 2014). When linked together, they produce a holistic framework for exploring the impacts of decarbonization.

This multi-tool framework is used to simulate the impacts of two decarbonization strategies. The first decarbonization scenario allows the model considerable flexibility in determining how to meet state mitigation goals. The second includes additional constraints that limit adoption of carbon capture and biomass technologies in New England, reflecting regional concerns about these technologies. While results are generated for the entire United States, the analysis is focused on the period of 2023 to 2050 and on Connecticut's eight counties: Hartford, Middlesex, Fairfield, New Haven, Tolland, Windham, Litchfield, and New London.

Scenarios

1. Reference Case

In this study, the Reference Case, or REF, is a conservative baseline scenario that includes only limited GHG mitigation measures through 2050. REF includes: the Regional Greenhouse Gas Initiative (RGGI), a cap on electric sector GHG emissions that has been adopted by 11 states in the Northeast US (RGGI, 2005); the Renewable Portfolio Standards (RPS) and Clean Energy Standards (CES) that had been adopted by states as of 2021 (NCSL, 2021); California's pre-

2022 light-duty electric vehicle (EV) sales targets for 2020 and 2025 (6% and 15%, respectively) by California and the 12 “Section 177” states (Advanced Clean Cars, 2022); and national light-duty EV sales estimates through 2030 to reflect anticipated impacts of the EPA’s Near-Term Light-Duty GHG Rule that was finalized in late 2021 (US EPA, 2015a). Additionally, REF accounts for New England's planned nuclear retirements through 2025 and offshore wind procurements in the Northeast US through 2030. Since RGGI’s CO2 targets have only been specified through 2030, we assume the 2030 cap is held constant through 2050.

Based on discussions with staff in the U.S. Environmental Protection Agency (US EPA) and the Connecticut Department of Energy and Environmental Protection (CT DEEP), REF also includes constraints that reflect the current energy landscape in the country and region. For example, the use of compressed natural gas (CNG) vehicles and advanced biofuels was limited to reflect current market conditions. In states that will have eliminated coal from the electric sector by 2023, it is assumed that no new coal electric generating units (EGUs) will be built, with or without carbon capture and storage (CCS). This constraint is applied to California, Connecticut, Idaho, Massachusetts, New Hampshire, New Jersey, New York, Oregon, Rhode Island, and Vermont. Additional capacity of conventional biomass combustion technologies in the electric sector is also limited, reflecting concerns about air pollutant emissions. Gasified biomass technologies are allowed, however, since these technologies are expected to have lower air pollutant emissions.

Furthermore, in states with explicit GHG reduction targets, it is assumed that no new industrial coal capacity will be built. This constraint applied to California, Colorado, Connecticut, Delaware, Louisiana, Massachusetts, Maryland, Maine, Michigan, Minnesota, Montana, North Carolina, New Hampshire, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, Virginia, Vermont, and Washington.

2. Decarbonization Case (DC1)

This scenario includes the policies listed in REF, but adds the following: state GHG reduction targets (represented as CO2 caps for groups of states) (Center for Climate and Energy Solutions, 2022); the new California Light-Duty vehicle electrification targets (100% sales share by 2035) , which are assumed to be adopted by all Section 177 states (Advanced Clean Cars, 2022); and the electrification targets specified by the Medium and Heavy Duty Electrification Memorandum of Understanding (100% by 2050) (NESCAUM, 2022). These policy representations are described in more detail below.

New State GHG Reduction Targets

This scenario includes GHG reduction goals from 23 states across the United States, implemented as economy-wide caps on CO2 emissions (Center for Climate and Energy Solutions, 2022). The states' commitments can be classified as statutory action (e.g., legislation) or legally binding executive action (e.g. a governor's executive order). The implementation does not take this difference in consideration and regards this as a best-case scenario where all states will fulfill these promises. Additionally, Wisconsin, Illinois, and Delaware have not been included since their decarbonization targets do not extend past 2025. To simulate impacts to the year 2050, we assume that the other states that have commitments that end after 2035 and prior to 2050 extend their final target through to 2050. Because of the stringency of some of these targets (e.g., several states required net-zero emissions by 2045), GCAM had difficulty simulating all the state targets simultaneously. To provide the model with additional flexibility, states with GHG targets within the same region of the country (e.g., Northeast, Southeast, Central, and West) are allowed to collectively meet their targeted reductions. This approach successfully addressed the problem of feasibility. However, this approach results in some states exceeding their specific state targets while others may not meet their targets. Specific state targets are listed in the Appendix.

New California Light-Duty Emissions Targets

California's new light-duty electrification targets are among the most stringent in the United States, aimed at reducing air pollution and greenhouse gas emissions from vehicles. Recently, California updated their EV targets to 100% sales by 2035. In this scenario, the other Section 177 states are assumed to follow suit and adopt the new target (Clegern, 2022).

Medium and Heavy-Duty Memorandum of Understanding

The transportation sector is the nation's largest source of greenhouse gas emissions, and accelerating the electrification of trucks and buses is essential to achieving deep decarbonization nationwide and protecting public health (US EPA, 2015b). Fifteen US states and the District of Columbia have signed a memorandum of understanding (MOU) to collaborate and accelerate the market for electric medium- and heavy-duty vehicles, including large pickup trucks and vans, delivery trucks, buses, and long-haul delivery trucks (NESCAUM, 2022). The MOU aims to ensure that 100% of all new medium- and heavy-duty vehicle sales are zero-emission vehicles by 2050, with an interim target of 30% zero-emission vehicle sales by 2030. The signatories include

California, Connecticut, Colorado, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington.

3. Decarbonization with PM Reductions (DC2)

This scenario is similar to the previously mentioned scenario, but with additional assumptions for New England that reflect insights from CT DEEP staff. Specifically, this scenario includes the following assumptions:

No New Biomass Electric Generating Units (EGU)

The use of biomass for electricity generation has not been widely adopted in New England and this trend is likely to continue (Wooster, 2010). One reason is the region's relatively high population density and the associated concerns about air pollution from biomass combustion. Additionally, many biomass-fueled power plants are not well-suited for load-following, which refers to the ability to adjust electricity output in response to changes in demand (EnergySage, 2022). This can make it difficult to balance electricity supply and demand in real-time, which can lead to higher costs and reduced system reliability. Furthermore, Connecticut staff indicated that snow and ice cover in the winter can complicate the management of biomass resources. As such, there currently is no plan to expand or create new biomass plants in New England, and biomass capacity additions in the electric sector are eliminated as an option for the region in this scenario.

No Carbon Capture and Storage (CCS)

New England has been reluctant to adopt carbon capture and storage (CCS) as a means of reducing greenhouse gas emissions. One of the reasons for this is the region's geology, which is not well-suited to underground storage of CO_2. The lack of suitable storage sites means that any CCS projects in the region would likely require the transportation of CO_2 over long distances, which can be expensive and can pose additional environmental risks. Additionally, there are concerns about the effectiveness of CCS in reducing emissions, the energy penalty associated with CCS, and concerns about pipelines, including high cost, siting, ownership, and operation. Given these challenges, many policymakers and experts in New England do not see CCS as a viable option to reach decarbonization targets, which is modeled here by eliminating CCS as an option in New England (Bonacini, 2021).

This study did not explicitly consider several factors during modeling, including the impacts of COVID-19 shutdowns and provisions of the Inflation Reduction Act of 2022 (The White House, 2022). The model also does not include state-specific energy efficiency and renewable energy policies beyond the Renewable Portfolio Standards, or regional greenhouse gas reduction strategies besides RGGI. The study also did not consider the impacts of New Source Review or Reasonably Available Control Technology (RACT), Best Available Control Technology (BACT), and Lowest Achievable Emission Rate (LAER) control requirements (US EPA, 2016a). Legal settlements between the EPA and companies that violate the Clean Air Act post 2015, the Cross-State Air Pollution Rule and Good Neighbor requirements were also not modeled in this study (US EPA, 2016a).

Modeling and Analysis

Emissions Modeling

GLIMPSE is a model-based tool for supporting long-term, coordinated air quality, energy, and climate planning that has been developed by the US EPA (US EPA, 2015). With GLIMPSE, users can evaluate new and emerging energy technologies, examine the efficacy of current and potential policies, and identify technology and fuel pathways for achieving air pollutant and GHG reductions goals.

The model used within GLIMPSE is the Global Change Analysis Model (GCAM). GCAM works by simulating the co-evolution of the energy, agricultural, water, and climate systems. A variant of GCAM, GCAM-USA is used in this application. GCAM-USA represents the US energy system at the state level including the technologies and fuels associated with energy demand, supply, transmission, and use. GCAM-USA allows users to analyze the impacts, interactions, and trade-offs among various policies or actions (Pacific Northwest National Laboratory, 1982).

The three scenarios, REF, DC1, and DC2, are modeled using GLIMPSE. The results were analyzed to assess changes in technology and fuel use, as well as the associated changes in emissions of particulate matter (PM2.5), sulfur dioxide (SO2), nitrogen oxides (NOX), ammonia (NH3), and volatile organic compounds (VOCs). The emissions data were then fed into COBRA. GCAM modeling was conducted by Dr. Dan Loughlin at EPA.

Health Impacts Modeling

The CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) is a health impact assessment tool that estimates the health impacts resulting from changes in air pollution (US EPA, 2020). The tool is based on a range of research papers and data sources, including the following:

1. Hospitalizations: Healthcare Cost and Utilization Project (HCUP), State Inpatient Databases (SID), the State Emergency Department Databases (SEDD), the Nationwide Inpatient Sample (NIS), and the Nationwide Emergency Department Sample (NEDS) (HCUP, 2013);
2. Mortality: Centers for Disease Control (CDC), National Center for Health Statistics (NCHS) (CDC, 2023);
3. Non-fatal heart attacks: Peters et al. (2001), Pope et al. (2006), and Sullivan et al. (2005), Rosamond et al. (1999);
4. Acute bronchitis: American Lung Association (2002); and,
5. Asthma: Ostro et al. (2001), American Lung Association (2010), Pope et al. (1991)

The specific health endpoints that will be examined in this study include the following:

1. Premature mortality: the number of deaths that can be attributed to air pollution for adults and infants;
2. Hospital admissions: hospitalizations that are directly or indirectly associated with exposure to PM;
3. Respiratory diseases: diagnoses include upper and lower respiratory distress, bronchitis, and asthma attacks; and,

4. Cardiovascular disease: diagnoses include non-fatal heart attacks.

Environmental Justice Analysis

The Environmental Justice Screening and Mapping Tool (EJScreen) is a tool used to analyze demographic and socioeconomic information at the county level (US EPA, 2014). EJScreen uses a variety of socioeconomic and environmental justice indices to assess the vulnerability of populations to environmental hazards, including air pollution. Some of the relevant indices that this study will examine include the following:

1. Minority and low-income: the percentage of the population identifying as minority and living below the poverty line; and,
2. Educational attainment: the percentage of the population over the age of 25 with less than a high school education.

These indices are only a few of the social, economic, and environmental factors that EJScreen reports. To better understand how changes in emissions resulting from decarbonization policies will affect actual communities, EJScreen results are plotted against health costs. The results of the EJScreen analysis will allow us to draw conclusions about how changes in air pollution from decarbonization policies could disproportionately impact certain communities in Connecticut.

RESULTS

Section 1: Emissions & Air Quality

Figure 1 depicts the carbon response to various decarbonization policies. The model shows that the largest reductions in CO_2 occur in electricity generation and highway emissions. The REF scenario estimates CO_2 emission reach 1.4 MTC in 2050, while the DC1 and DC2 scenarios show reductions of 0.3 and 0.4 MTC respectively. Notably, while electric sector carbon emissions go down in the DC1 scenario, carbon emissions from biomass combustion in electricity generation increase fourfold relative to Base and DC2. Highway emissions in the REF scenario are expected to be 2 MTC. The DC1 scenario reduces these emissions 10-fold, as does the DC2. This trend is consistent with recent legislative efforts to electrify light-duty vehicles and commercial fleets using medium and heavy-duty vehicles. Across the sectors, the DC2 scenario does not show significant carbon reductions as limiting biomass and CCS is likely to have a large impact on other pollutant species.

The Bio-Ag category reflects the carbon that is removed from the atmosphere during the growth of biomass that is used for bioenergy purposes, including combustion in powerplants and industry, as well as feedstock for biofuel production. These negative emissions grow to -1.5 MTC in DC1, while the DC2 scenario shows numbers similar to the REF scenario.

Figure 2 illustrates the annual emissions of five pollutant species (NO_x, SO_2, VOC, NH_3, and PM2.5) by county, for the years 2023 and 2050, that result from the decarbonization scenarios. In 2023, Hartford and Fairfield counties were found to be major contributors to NO_x and SO_2 emissions, collectively accounting for nearly 50% of total emissions in Connecticut. In the DC1 and DC2 scenarios, all counties exhibited reductions in emissions that were approximately proportional to each other. The decarbonization policy was observed to have the greatest effect on NO_x, SO_2, and NH_3, while VOC and direct PM2.5 saw limited reductions through decarbonization. It is important to note that this these graphs only show changes in emissions in

Connecticut. Emissions changes are also occurring in states upwind of Connecticut, impacting overall air quality in Connecticut.

Figure 3 shows emissions of the pollutant species by sector in Connecticut. Electricity generation in the DC1 scenario is associated with large increases in SO_2 of 1416 tons and PM2.5 of 1272 tons, and a modest increase in NH3 of 99 tons. Meanwhile, eliminating biomass in the DC2 scenarios led to a sizable decrease as compared to REF. PM2.5, SO_2, and NH_3 decreased by 39 tons, 36 tons, and 89 tons respectively. Residential PM2.5 emissions are expected to be high at 3404 tons and increased in both DC1 and DC2 scenarios by approximately 10%. Residential emissions for NO_x, SO_2, and NH_3 decreased however. The most dramatic changes were observed in transportation, with a sixfold decrease in VOC and a 10-fold decrease in NH_3.

Figure 4 shows the expected PM2.5 levels in Connecticut in 2050, and expected changes in concentration. Fairfield is expected to have the highest concentrations of PM2.5 while Litchfield will have the lowest. The overall state PM2.5 concentrations range from 4.8-6.2 ug/m^3. Under DC1 scenarios, PM2.5 increases in all counties except for Fairfield, which sees a small decrease of 0.005 ug/m^3. Tolland and Windham counties have the highest deterioration in air quality both around 0.05 ug/m^3. Thus, the DC1 result is counter to the assumption that decarbonization will yield air quality co-benefits. In contrast, the DC2 scenario, which does not allow the decarbonization strategy in New England to include biomass or CCS, shows improved air quality in half of the counties, namely Fairfield, Hartford, Middlesex, and New Haven. While the remaining counties show an increase in PM2.5 concentrations, this increase is less than half of the increase in the DC1 scenario.

Figure 5 illustrates the variations in NO_x and SO_2 emissions in 2050 across Pennsylvania, Ohio, West Virginia, New York, and New Jersey. These states are anticipated to exert the most significant influence on Connecticut's air quality, in the order listed. The selection of these states was based on a sensitivity analysis that involved a 10% reduction in each state's electric sector emissions for all five pollutants and a comparison of the resulting impacts on health impacts in Connecticut. The resulting expected monetary health benefits for Connecticut can be found in the Appendix.

Substantial reductions in emissions were observed in Pennsylvania, with NO_x levels declining by approximately 38 thousand tons and SO_2 levels decreasing by 2,300 tons under the DC1 scenario. Notable declines in NO_x were also recorded in New York and New Jersey, while minor increases were observed in West Virginia and Ohio. This result is consistent with expectations since West Virginia and Ohio have not specified state GHG reduction targets, and thus there is emission "leakage" from those states with targets.

The DC2 scenario appears to exert a more pronounced influence on SO_2 emissions, as evidenced by West Virginia transitioning from a 240-ton increase to a 1,600-ton decrease upon the exclusion of biomass and CCS. Although power sector emission reductions from Ohio and West Virginia were estimated to have a large impact on Connecticut, the DC1 and DC2 models do not appear to show this association. This is likely because Ohio and West Virginia have not published updated GHG targets and both states possess substantial industrial sectors which were not modeled in GCAM (Center for Climate and Energy Solutions, 2022).

Figure 1. *Carbon response in Connecticut to various policies. Graph highlights the most significant reductions occur in electricity generation and highway emissions.*

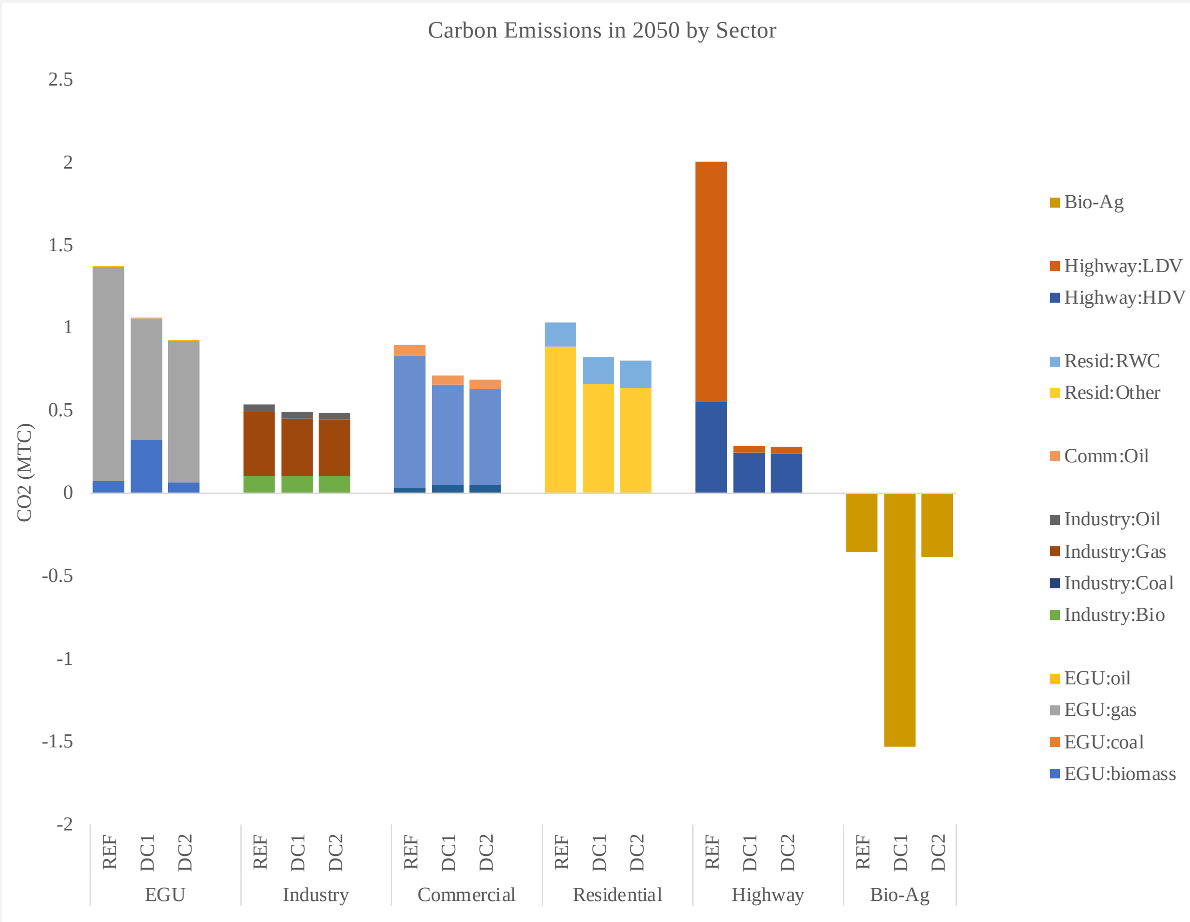


Figure 2. *Annual emissions of five pollutant species (NO_x, SO_2, VOC, NH_3, and PM2.5) by county in Connecticut. Emissions are shown for 2023 and 2050 for the different decarbonization scenarios.*

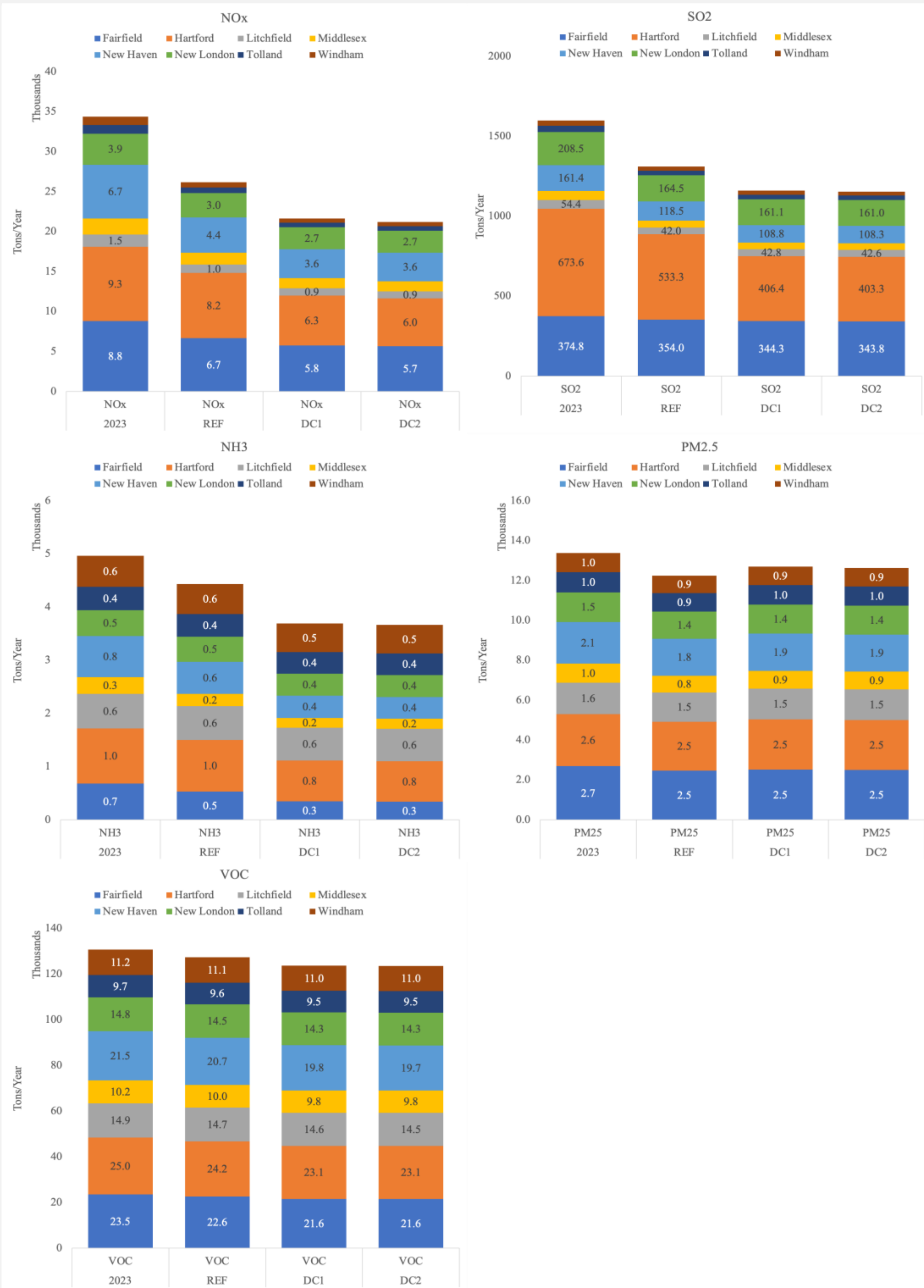
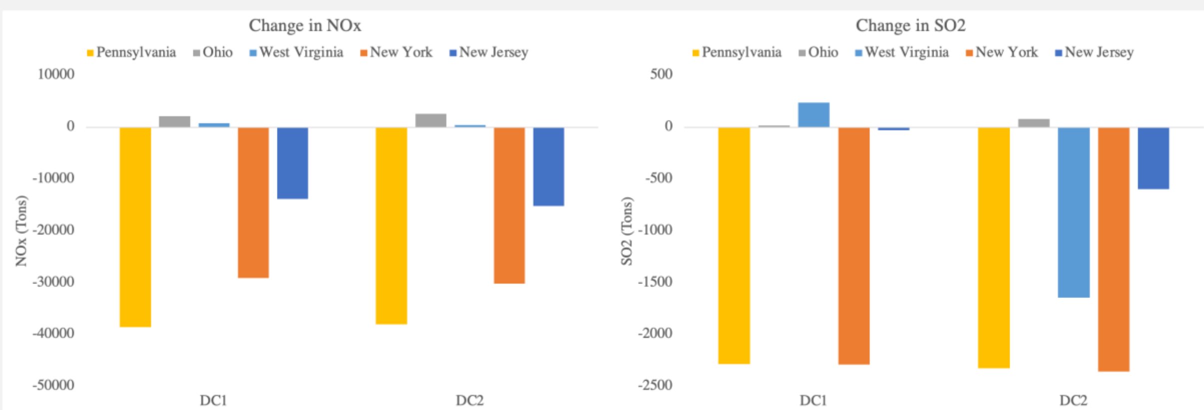


Figure 3. *Annual emissions by sector in Connecticut in 2050. Electricity generation shows the largest change across scenarios.*

Figure 4. *PM2.5 levels in Connecticut and changes with decarbonization scenarios in 2050. Concentration changes are most pronounced in DC2.*

Figure 5. *Change in NO_x and SO_2 in neighboring states with the greatest estimated impact on Connecticut air quality in 2050. Shown below are Pennsylvania, Ohio, West Virginia, New York, and New Jersey.*



Section 2: Health Impacts

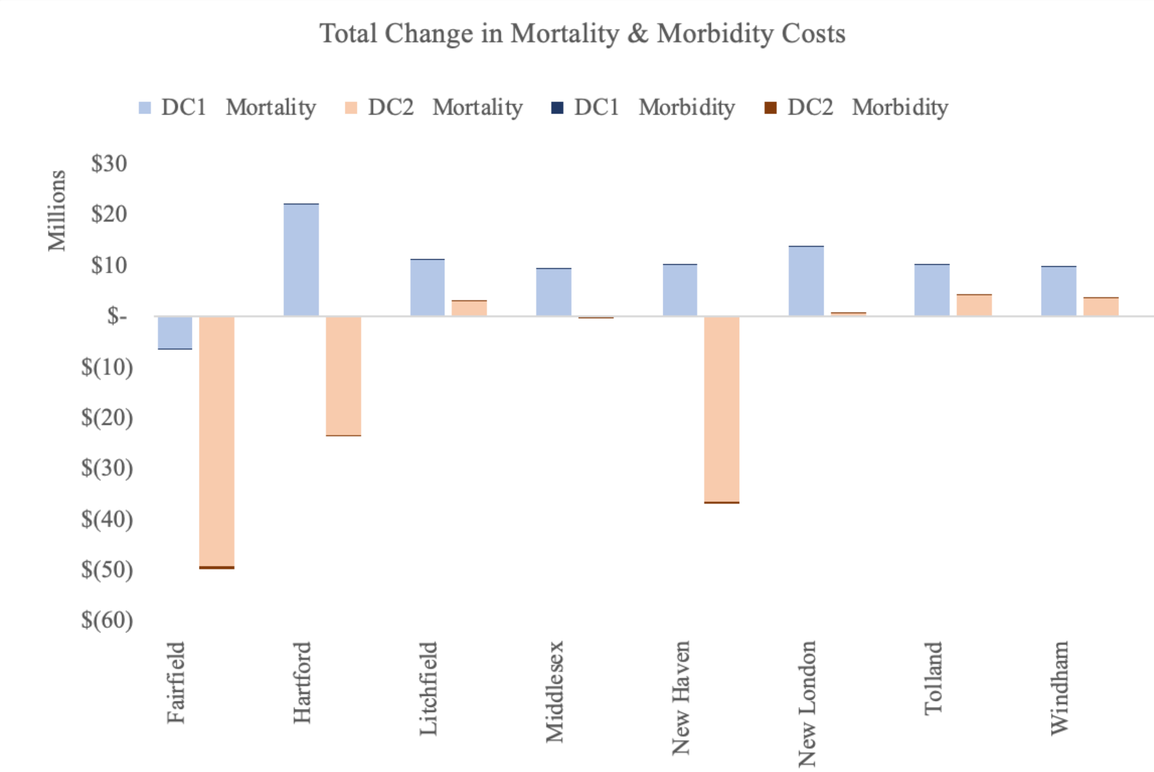
Figure 6 shows the change in total mortality and morbidity costs for each scenario in 2050 with most of the costs or benefits coming from mortality. Under the DC1 scenario, the state of Connecticut is expected to see a net $79.7 million in additional mortality costs and $960 thousand in additional morbidity costs, relative to the Reference scenario. Across the counties, Hartford has the highest increase in health costs, at $22.2 million. When examining the DC2 scenario, expected health benefits for the state are $98.2 million for mortality and $1.2 million for morbidity. The DC2 scenario leads to health benefits in Fairfield, Hartford, Middlesex, and New Haven. Fairfield and New Haven will see the largest benefits of $50 million and $37 million respectively. These results reflect the importance of considering PM2.5 changes when implementing any clean energy initiatives.

Figure 7 displays the total hospitalizations associated with respiratory and cardiovascular (excluding heart attacks) illnesses, with the state average for DC1 showing an increase of 0.33 cases per million for combined respiratory and cardiovascular hospitalization. The DC2 scenario shows the reverse of these results, with 0.35 cases per million avoided. Overall hospitalizations for direct and indirect respiratory conditions are low, and many respiratory conditions are treated in outpatient facilities. Additionally, those who are hospitalized due to respiratory distress often present co-morbidities that are prioritized at time of admission and triage. As a result, documenting and attributing air pollution directly to hospitalizations continues to be a challenge.

Figure 8 shows more common respiratory diseases in the form of asthma, upper respiratory, and lower respiratory symptoms. Under the DC1 scenario, cases increased in all counties except for

Fairfield with the highest in Windham of 13 cases per 100K. Notably cases of respiratory distress are likely underreported due to adults and children choosing to treat with over-the-counter medications. This study also considers the total population of Connecticut which may not reflect the heterogeneity in air pollution vulnerability. Previously cited studies have shown children and elderly are more susceptible to PM2.5 associated diseases, and this may be an area for further study.

Figure 6. *Costs associated with mortality and morbidity in Connecticut. Monetary values are reported in 2017$. The top graph shows total costs and bottom shows per capita costs in 2050.*



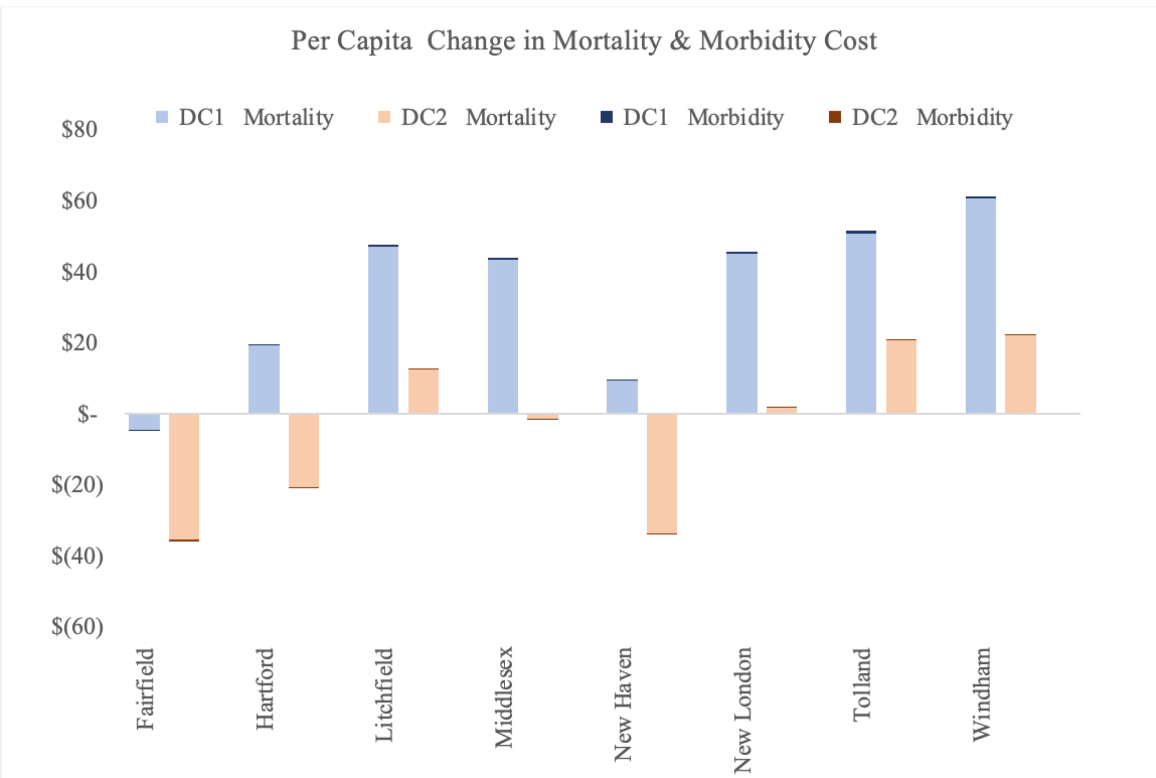


Figure 7. *Change in hospitalizations cases per million people. This graph shows cases for both respiratory and cardiovascular hospitalizations. Hospital cases are overall low.*

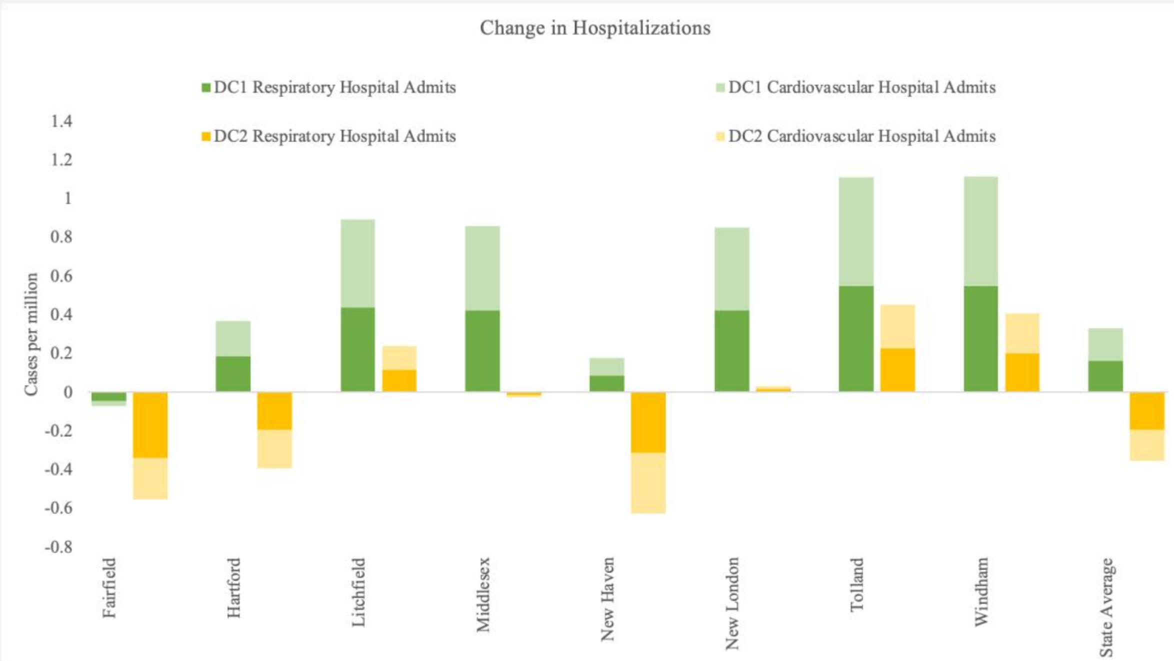
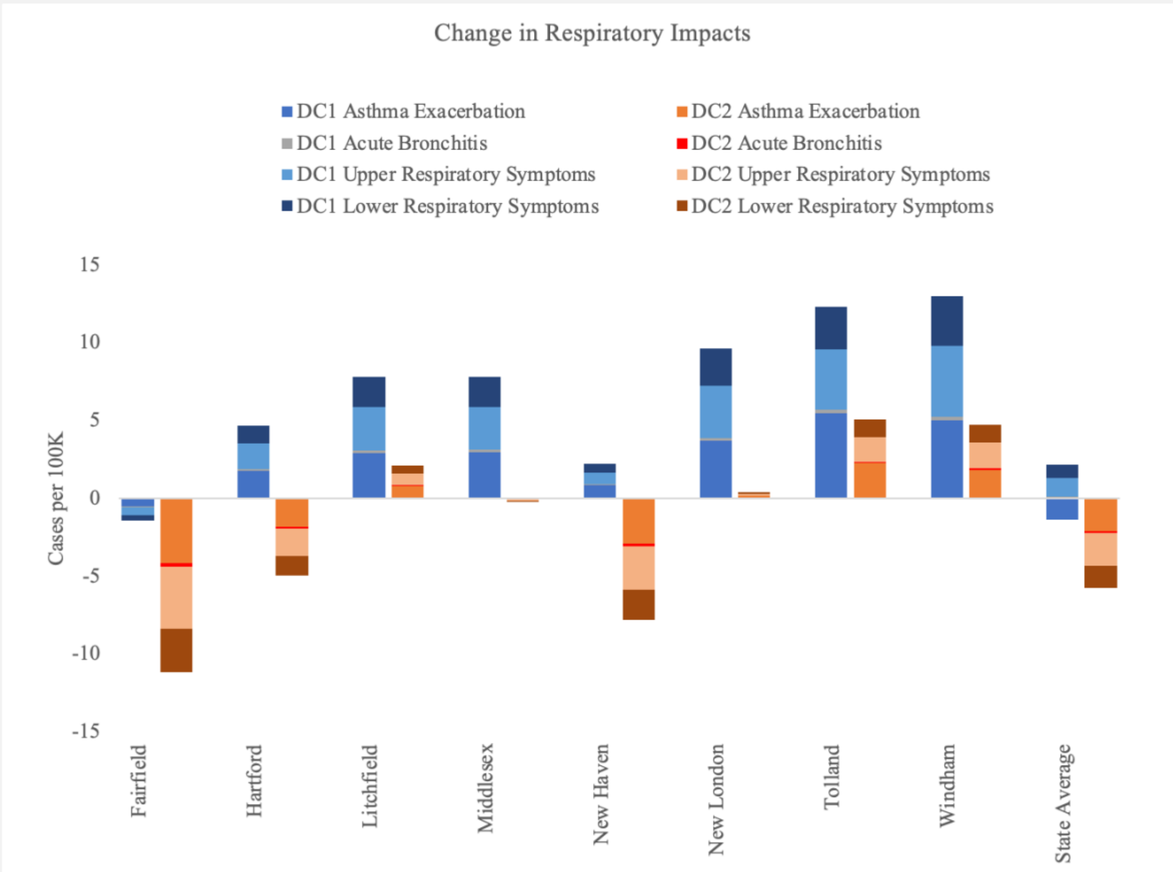


Figure 8. *Change in respiratory related diseases in cases per 100K people in 2050. Asthma and bronchitis are more common respiratory related ailments which expect to see increases under DC1.*



Section 3: County Demographics & Environmental Justice

Figure 9 provides demographic information for Connecticut, with the state reporting an average of 34% low minority residents, 22% low-income residents, and 6% with less than a high school education. Fairfield, Hartford, and New Haven counties have up to 40% residents that identify as people of color, and these are the counties that are modeled to receive the greatest benefit from the DC2 scenario.

Figure 10 delves deeper into the link between demographics and mortality costs. First examining total mortality costs, DC1 shows a limited correlation between the health benefits and the percentage of minority population, as evidenced by a correlation coefficient of -0.07. This suggests that the distribution of health co-benefits in this scenario is not strongly associated with minority populations. However, in DC2, the health benefits are highly correlated with the minority population, as demonstrated by a correlation coefficient of -0.87. This indicates that areas with a higher percentage of minority populations may experience greater health benefits under a scenario where biomass and CCS are limited. Specifically, New Haven, Fairfield, and Hartford are expected to see the greatest benefits. When the costs are reported per capita, both DC1 and DC2 show a high correlation between minority percentage and mortality costs. This is evidenced by a correlation coefficient of -0.85 for DC1 and -0.87 for DC2. Overall, these results indicate that special attention should be paid to minority populations when designing public health interventions.

Figure 9. *Demographic information for each county by percentage minority, low income, and those who did not complete high school. Minority populations appear to be more heterogenous across the state as compared to income and education.*

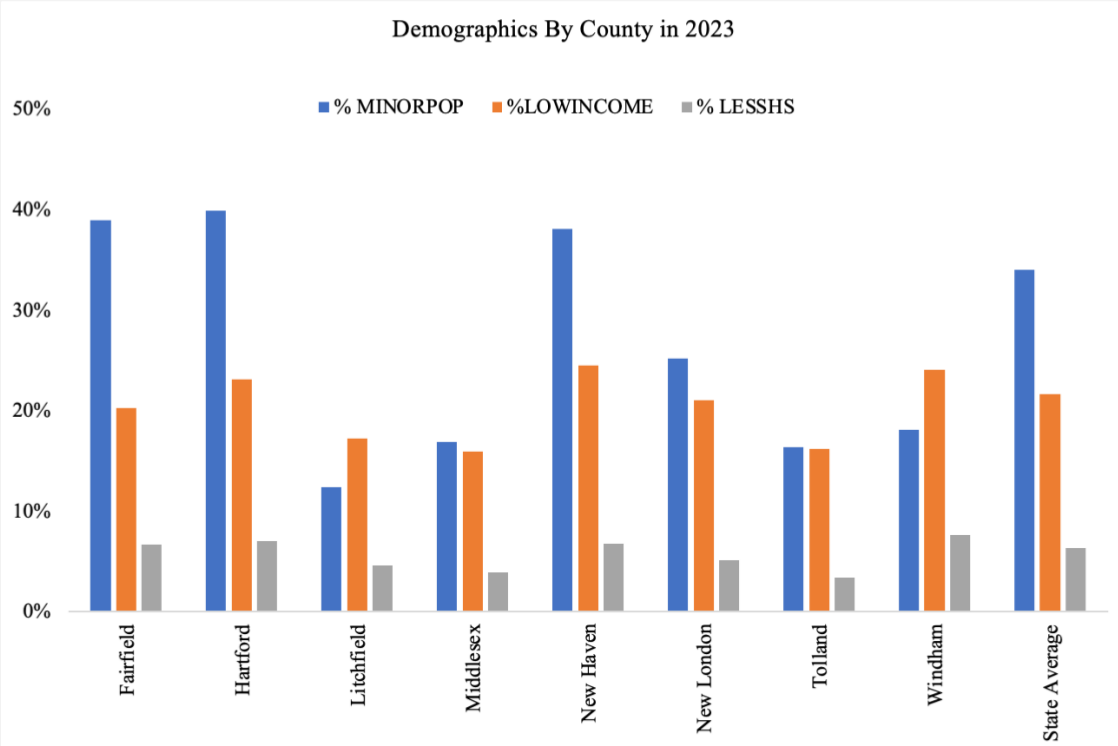
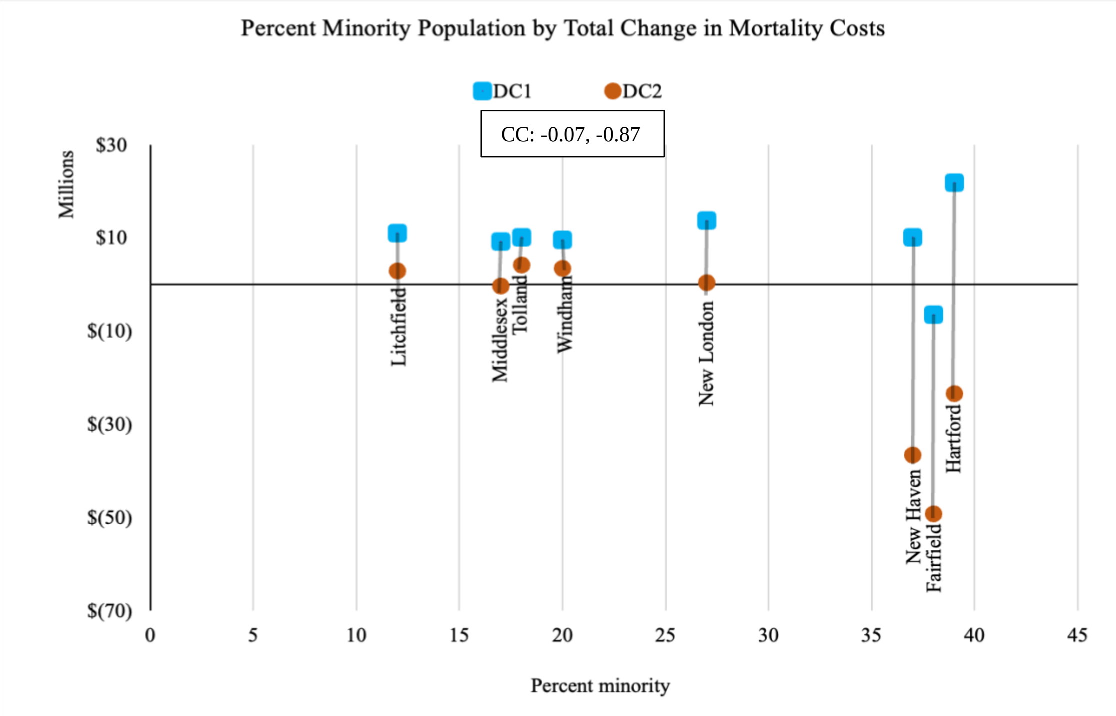
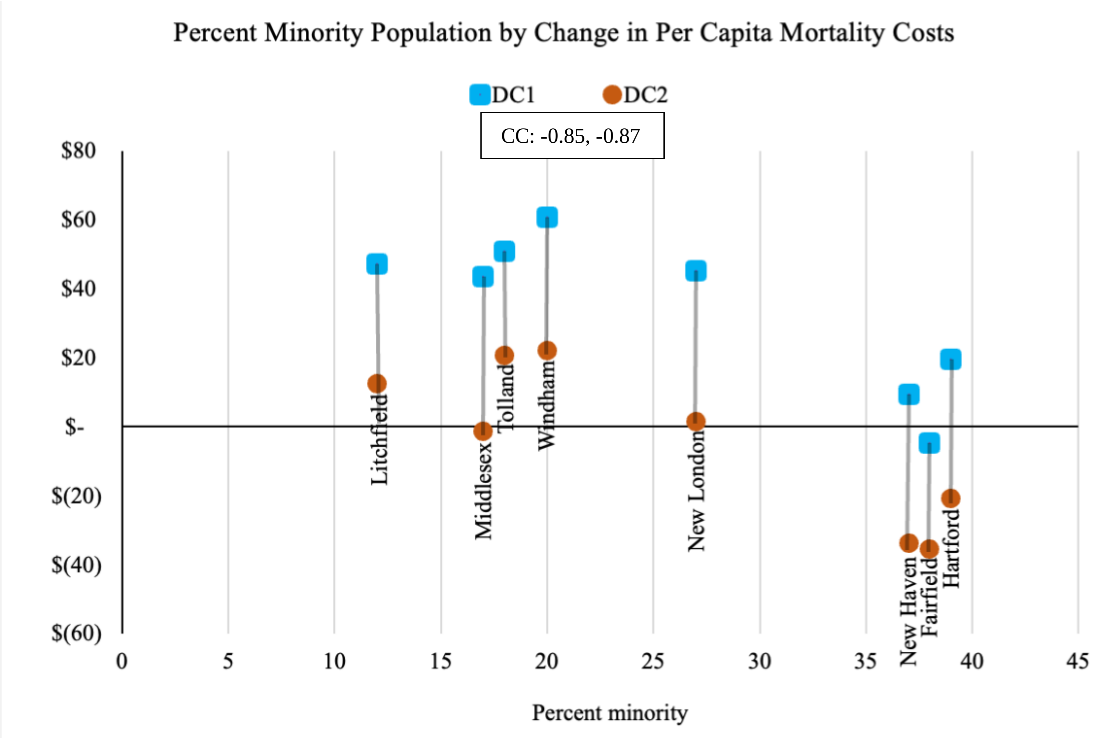


Figure 10. *Difference in change of mortality costs between DC1 and DC2 in total costs and per capita. Note that the demographic information is from 2023, while the mortality costs are those expected in 2050.*





CONCLUSION

Summary of Major Findings

The analysis of emissions and air quality demonstrated that Connecticut may benefit greatly from more ambitious regional carbon reductions – if decarbonization pathways are chosen that do not increase PM emissions. The state also shows variability in air quality between counties. Hartford and Fairfield counties are expected to be the primary contributors of NO_x, SO_2, VOC, NH_3, and PM2.5 emissions. The implementation of decarbonization policies was most effective in reducing NOx, SO2, and NH3 emissions, while reductions in VOC and direct PM2.5 were comparatively limited. Notable CO_2 emission reductions were observed in the electricity generation and highway sectors. However, the DC1 scenario, which incorporated biomass and CCS as mitigation options in New England, resulted in a four-fold increase in carbon emissions due to biomass combustion. On the other hand, the DC2 scenario did not lead to substantial carbon reductions but contributed to significant decreases in SO_2, PM2.5, and NH_3 emissions when compared to the DC1 scenario.

In terms of health impacts, the DC1 scenario led to a marked increase in both mortality and morbidity costs, primarily driven by mortality. DC1 scenario showed an increase in respiratory distress cases in all counties except Fairfield, with the highest increase recorded in Windham. Conversely, the DC2 scenario yielded substantial health benefits for both mortality and morbidity. Health benefits in the DC2 scenario were most pronounced in Fairfield, Hartford, Middlesex, and New Haven counties, with the largest benefits observed in Fairfield and New Haven. These outcomes emphasize the necessity of accounting for PM2.5 changes when devising clean energy policies.

Demographic data revealed that up to 40% of residents in Fairfield, Hartford, and New Haven counties identify as people of color. These counties were projected to receive the most significant benefits from the DC2 scenario. Under the DC1 scenario, the correlation between health costs and the percentage of minority population was limited. However, in the DC2 scenario, a strong correlation emerged between health benefits and minority population percentages. The correlation was strong for both DC1 and DC2 when costs were reported per capita. This finding suggests that decarbonization policies are effective across the board, and may be even more effective for minority populations when constraining PM.

Limitations of the Study

There are several limitations in this study that need to be acknowledged. First, the research utilizes a screening methodology that incorporates a range of simplifying assumptions. Certain targets could not be modeled at the state level, and regional targets were assumed. This analysis also does not encompass all policies that could potentially impact emissions. Evolving legislation also means that targets may have a shorter or longer time horizon than modeled in this study. Furthermore, this study does not take into account changes in emissions from tribal regions and sources outside US boundaries. We assume air quality changes from sources to be linear and additive, neglecting the nonlinear atmospheric chemistry and the non-additive interactions among various pollutants and emissions from distinct sources.

This study also did not evaluate the health impacts of indoor air quality, as COBRA is only capable of assessing outdoor air quality. COBRA also relies on several robust research papers to estimate its health impacts, and this study assumed these indices to stay constant into 2050. However, changes in behavior, economics, and climate in the coming years will likely change the rate of disease. Finally, COBRA should only be used as a screening tool, and issues such as cap implications and assumptions about statewide percentage reductions might be oversimplifications.

EJScreen is another screening tool which provides a easily digestible view of demographic information. However, it does not provide an in-depth risk analysis and only examines a subset of environmental justice issues. Due to limitations in data quality, coverage, and resolution, many environmental concerns are not included in comprehensive nationwide databases from which EJScreen draws upon. EJScreen depends on estimates that entail uncertainty particularly when examining small geographic areas such as the counties examined in this study.

Next Steps

In the next steps of this research, several avenues of investigation can be pursued to further expand our understanding of the link between decarbonization and health co-benefits. These future research directions are outlined below:

Policy Isolation: A more in-depth analysis of the policies contributing to health benefits or disbenefits can be conducted to identify the most effective strategies for achieving both decarbonization and public health goals. By isolating and evaluating the impact of individual policies, policymakers can prioritize actions that maximize health co-benefits and minimize any potential negative consequences.

National Projections Comparison: To contextualize the findings of this study, it would be valuable to compare the case numbers obtained from the research to national projections. This comparison would provide insights into how Connecticut's decarbonization efforts and health co-benefits align with broader trends, and whether the state's progress is on par with, ahead of, or lagging behind the national trajectory.

Impact of Emissions from Other States: Another area of interest is exploring the influence of emission changes in neighboring states on Connecticut's air quality and health outcomes. While this study did present changes in SO_x and NO_x in relevant states, the analysis did not extend to the impact emission changes will have on Connecticut. Meteorological and atmospheric analysis would enable a more comprehensive understanding of regional emission dynamics and their cross-border implications, which could inform cooperative strategies for air quality management.

By addressing these research directions, future work can build upon the findings of this thesis and contribute to a more comprehensive understanding of the interplay between decarbonization efforts, health impacts, and environmental justice. This knowledge will be crucial in guiding policymakers and stakeholders toward more effective and equitable strategies for transitioning to a low-carbon future while maximizing public health benefits.

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APPENDIX

I. State GHG Targets (Center for Climate and Energy Solutions, 2022)

Northeast

- Connecticut enacted a statutory target in 2018 to reduce GHG emissions 45% below 2001 levels by 2030 and 80% by 2050.
- Massachusetts enacted a statutory target in 2021 to reduce GHG emissions 85% below 1990 levels by 2050.
- Maine set an executive target in 2019 to achieve net-zero GHG emissions by 2050, and enacted statutory targets to reduce GHG emissions 45% below 1990 levels by 2030 and 80% below 1990 levels by 2050.
- Vermont enacted statutory targets in 2020 to reduce GHG emissions 26% below 2005 emissions by 2025, 40% below 1990 levels by 2030, and 80% below 1990 levels by 2050.
- Rhode Island enacted statutory targets in 2021 to reduce GHG emissions 10% by 2020, 45% by 2035, and 80% by 2040, all compared to 1990 levels. The targets also aim for net-zero GHG emissions by 2050.
- Pennsylvania set executive targets in 2019 to reduce GHG emissions 26% below 2005 levels by 2025 and 80% below 2005 levels by 2050.
- New York enacted statutory targets in 2019 to reduce GHG emissions 40% below 1990 levels by 2030 and at least 85% below 1990 levels by 2050.
- New Jersey enacted statutory targets in 2007 to reduce GHG emissions to 1990 levels by 2020 and 80% below 2006 levels by 2050.

Mid-Atlantic

- Maryland enacted a statutory target in 2016 to reduce GHG emissions 40% below 2006 levels by 2030 and net-zero target by 2045.
- Virginia enacted a statutory target in 2020 to achieve net-zero GHG emissions across all sectors by 2045.
- North Carolina set an executive target in 2022 to reduce GHG emissions 50% below 2005 levels by 2030.

Central

- Michigan set an executive target in 2020 to achieve economy-wide carbon neutrality by no later than 2050.
- Maine set an executive target in 2019 to achieve net-zero GHG emissions by 2050, and enacted statutory targets to reduce GHG emissions 45% below 1990 levels by 2030 and 80% below 1990 levels by 2050.
- Louisiana set executive targets in 2020 to reduce net GHG emissions 26–28% by 2025 and 40–50% by 2030.

West

- California set an executive target in 2018 to reach net-zero carbon dioxide emissions by 2045.
- Oregon set executive targets in 2020 to reduce GHG emissions 45% below 1990 levels by 2035 and 80% below 1990 levels by 2050.
- Washington enacted statutory targets in 2020 to reduce GHG emissions 45% by 2030, 70% by 2040, and 95% by 2050, all compared to 1990 levels.

- New Mexico set an executive target in 2019 to reduce GHG emissions 45% below 2005 levels by 2030.
- Colorado enacted statutory targets in 2019 to reduce GHG emissions 26% by 2025, 50% by 2030, and 90% by 2050.
- Montana set an executive target in 2019 to achieve economy-wide GHG neutrality with no set target year; in 2020, the state set the target year to reach economy-wide GHG neutrality between 2045–50.

II. Regional Emissions Impact on CT

State	Total Health Benefits for CT
PA	$14,275,105
OH	$12,292,003
WV	$12,145,724
NY	$11,578,349
NJ	$6,098,143
MI	$5,533,893
IN	$5,067,767
NC	$4,591,145
IL	$2,560,906
VA	$1,831,134
MD	$1,495,073