Health-Aware Optimal Power Flow: Accounting for Public Health in Energy Management

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1.1: Background

Energy Generation poses significant risks to Public Health

- The 3,400+ fossil fuel-fired power plants in the US are the largest source of nitrogen oxides (NO_x), which form ground level ozone, and sulfur dioxides (SO_2), which form fine particulate matter[1,2,3]
- Ground-level ozone and fine particulate matter emitted by power plants lead to increased heart attacks, asthma attacks, strokes, premature death, and other serious health effects[1,2,3]

1.2 Optimal Power Flow (OPF)

Optimal Power Flow (OPF) Management
Independent system operators use optimal power flow (OPF) models to manage the power grid, which minimizes economic cost of grid operation subject to the physical constraints of the power grid[4].

Outlined here is DC-OPF, a special case of OPF which linearizes power flows, making this model easier to solve[4].

$$\min \sum_i c_i P_{G_i}$$

$$\text{s.t.} \quad P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max} \quad \text{(power balance constraint)}$$

$$\mathbf{B} \cdot \theta = \mathbf{P_G} - \mathbf{P_D} \quad \text{(net injection at each bus)}$$

$$\frac{1}{x_{ij}}(\theta_i - \theta_j) \leq P_{ij,max} \quad \text{(injection line flow relations and line limits)}$$

Carbon-Aware Optimal Power Flow Modeling
Previous literature by Chen et al. accounted for carbon emissions associated with energy generation[5] by penalizing total carbon emissions in their cost function and adding carbon flow constraints to track movement of carbon emission costs through power grid.

2.2: Determining Health Cost

COBRA[6]
Co-Benefits Risk Assessment
Health Impacts Screening and Mapping Tool

1. Input: change in emission levels of
   - fine particulate matter ($PM_{2.5}$) (primary emission)
   - precursors of secondary $PM_{2.5}$ and ozone (O_3): nitrogen oxides (NO_x) sulfur dioxide (SO_2), volatile organic compounds (VOCs)

Models air-dispersion of pollutant sources at the county level through a Source-Receptor Matrix, which acts like a transfer function[7]

Determines changes in various health effects tied to specific air pollutants based on current epidemiological study.[7]

Output: overall health benefit and per county health benefit of input scenario

Overview
Air pollution emitted by fossil fuel-fired power plants pose a significant risk to public health. Yet, no current optimal power flow models consider the health impacts of grid management decisions. Thus, we aim to minimize the negative health effects associated with power generation. We introduce a Health-Aware Optimal Power Flow (H-OPF) model, which minimizes the combined economic cost of grid operation and public health impact. We examine a synthesized power grid managed using the H-OPF, Carbon-Aware OPF, and DC-OPF schemes, respectively, and find the H-OPF model significantly lowers health impacts of the power grid at a relatively small increase in economic cost.

3.1: Experimental Setup

Test Grid: EPIGRIDS-New England 250-bus system (NE-250)[10]
- Synthesized to roughly mimic the actual population of its geographic footprint
- 180 unique geographic bus locations
- 42 Generators:
  - 29 Natural Gas (NG)
  - 5 Oil (RFO)
  - 4 Nuclear (NUC)
  - 3 Coal (BIT)
  - 1 Wind (WND)
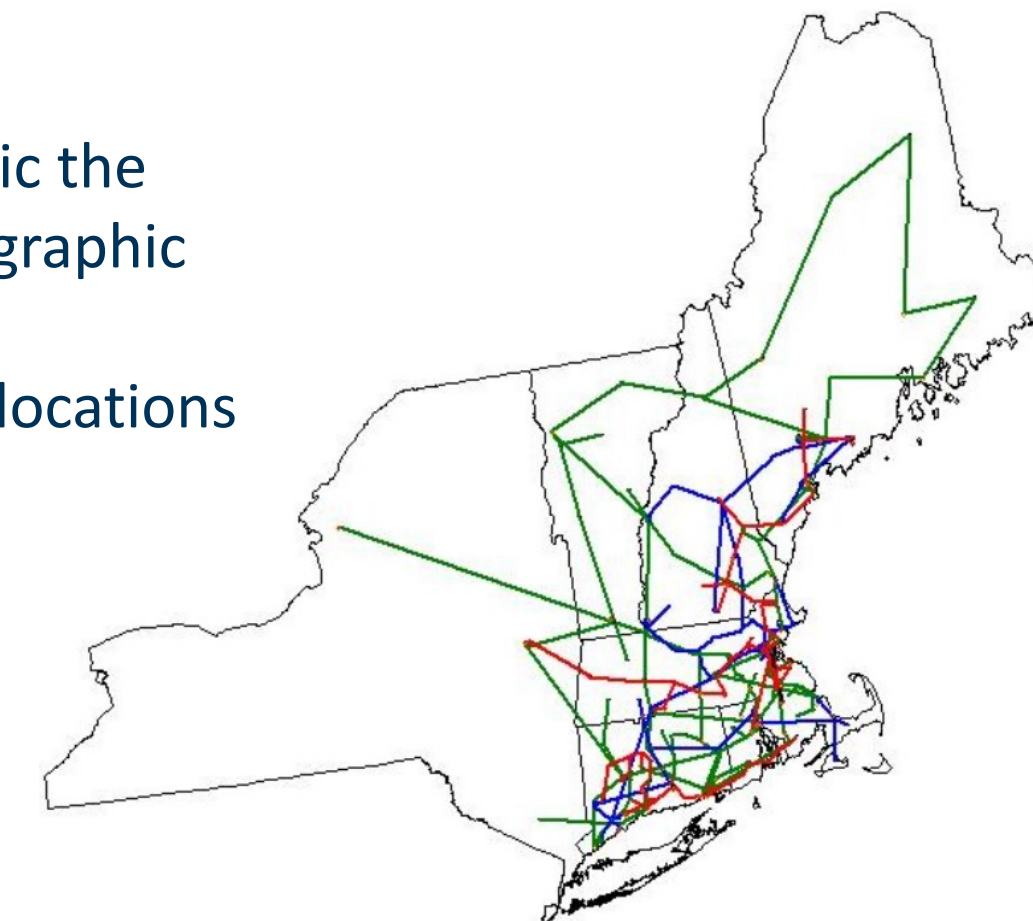
1. Used EPA eGrid 2021 emissions data[8] to assign emission rates to synthesized grid

2. Created COBRA scenario files by sampling test grid emissions levels according on capacity of synthesized grid

3. Ran 1000 COBRA scenarios, labeled emissions data with health cost

4. Ran linear regression to learn linear health cost function of test grid (r^2=1)

5. Used MATPOWER[9] to run DC-OPF simulation using the health cost function, carbon cost function, economic cost function, and a linear combination of the three, respectively.

3.2 Results

Change in load from cost to health optimization

Legend:
- Natural Gas
- RFO
- WND
- BIT
- NUC
- load decreased
- load increased

Accounts for air dispersion of sources

i: Difference in generator load decisions between H-OPF and cost-based DC-OPF. Load decreases around more populous areas such as Boston, MA, and Portland, ME, and increases around less populous rural areas.

ii: Public health benefit per hour (in thousands of 2023 dollars) by county over standard economic dispatch for (a) H-OPF and (b) C-OPF. While the health benefits from H-OPF and C-OPF are correlated, H-OPF has larger health benefits. H-OPF sees no decrease in health benefits among rural counties where load increased. increased.

public health benefit ($, thousands) 0–15

(a) H-OPF   (b) C-OPF

2.1 Health- Aware OPF

A standard, non-health-aware OPF scheme historically uses the economic cost of generation as the objective. This operational cost of power generation function is parametrized as a quadratic cost function for each generator:

$$f_{power} := \sum_{i \in \mathcal{N}} \sum_{g \in \mathcal{G}_i} c_{i,g}^2 (P_{i,g}^G)^2 + c_{i,g}^1 P_{i,g}^G + c_{i,g}^0,$$

Ambient air pollution is affected by air dispersion around an emission source. Thus, health impact is dependent on both location and intensity of emissions. We consider a public health cost function whose value depends on generator decisions, emissions intensities, and location specific public health costs. Here, c^m denotes the public health cost of emission m at node i, and w represents the emission intensity of emission m at node i and generator g:

$$f_{emission} := \sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{N}} c_i^m \cdot \sum_{g \in \mathcal{G}} \omega_{i,g}^{G,m} P_{i,g}^G,$$

System operators are likely to optimize some combination of these costs to account for both the cost of generation as well as the social and health cost of various emissions. Thus, our H-OPF framework seeks to minimize the overall objective:

$$\alpha f_{power} + \beta f_{carbon} + \gamma f_{emission},$$

With hyperparameters α, β, and γ representing tradeoff between economic, health, and carbon cost in the optimization.

4: Future Directions

Add Health Specific Flow Constraints to model
By relating health impact with physical power flow, we can track how health impact moves through the grid and corresponds to the demand of specific users.

Analyze effect of renewable energy sources and energy storage
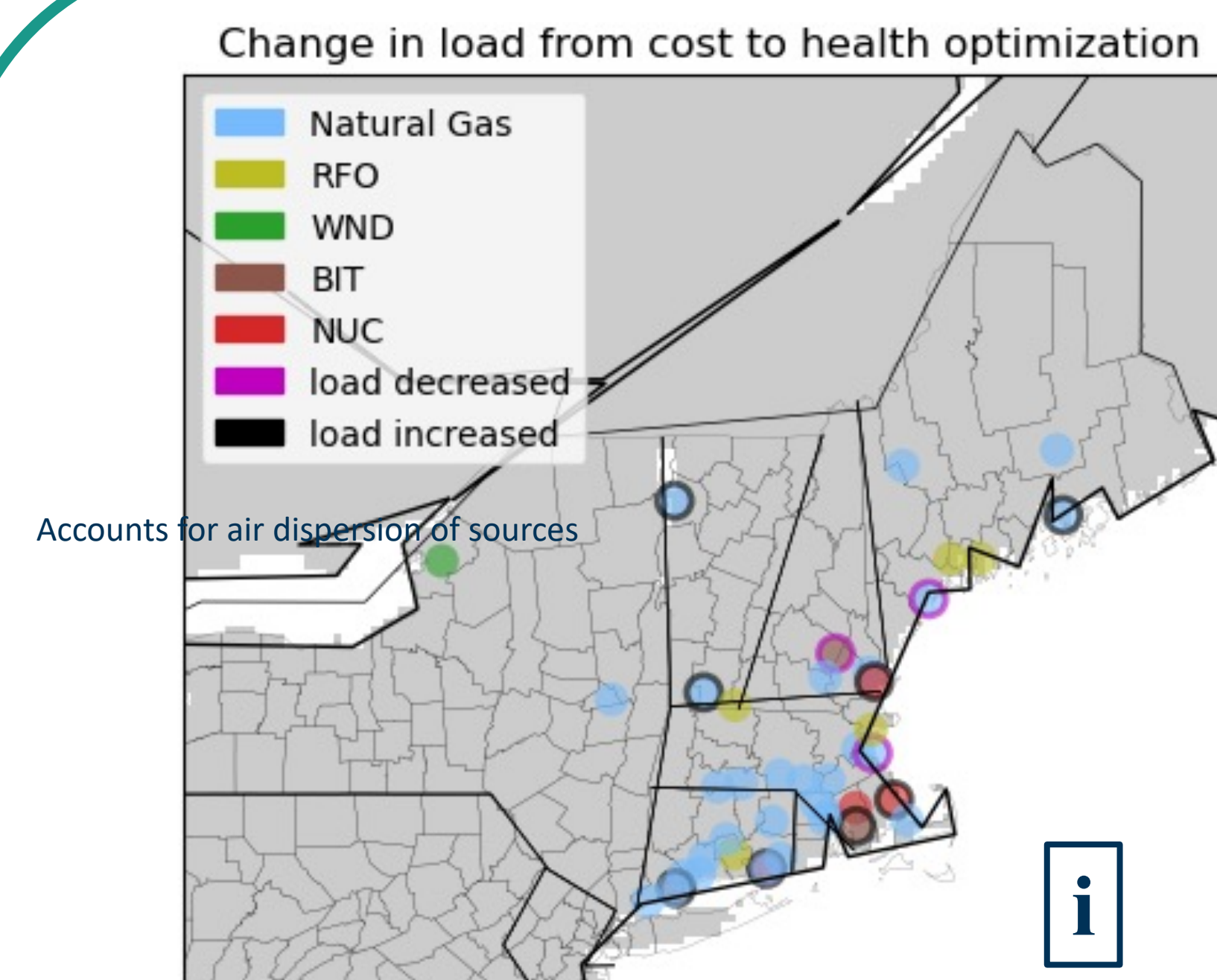Renewable energy sources contribute fewer overall emissions and can help lower the health impact of the grid. We want to understand how the placement of these plants can impact their efficacy under the H-OPF management strategy.
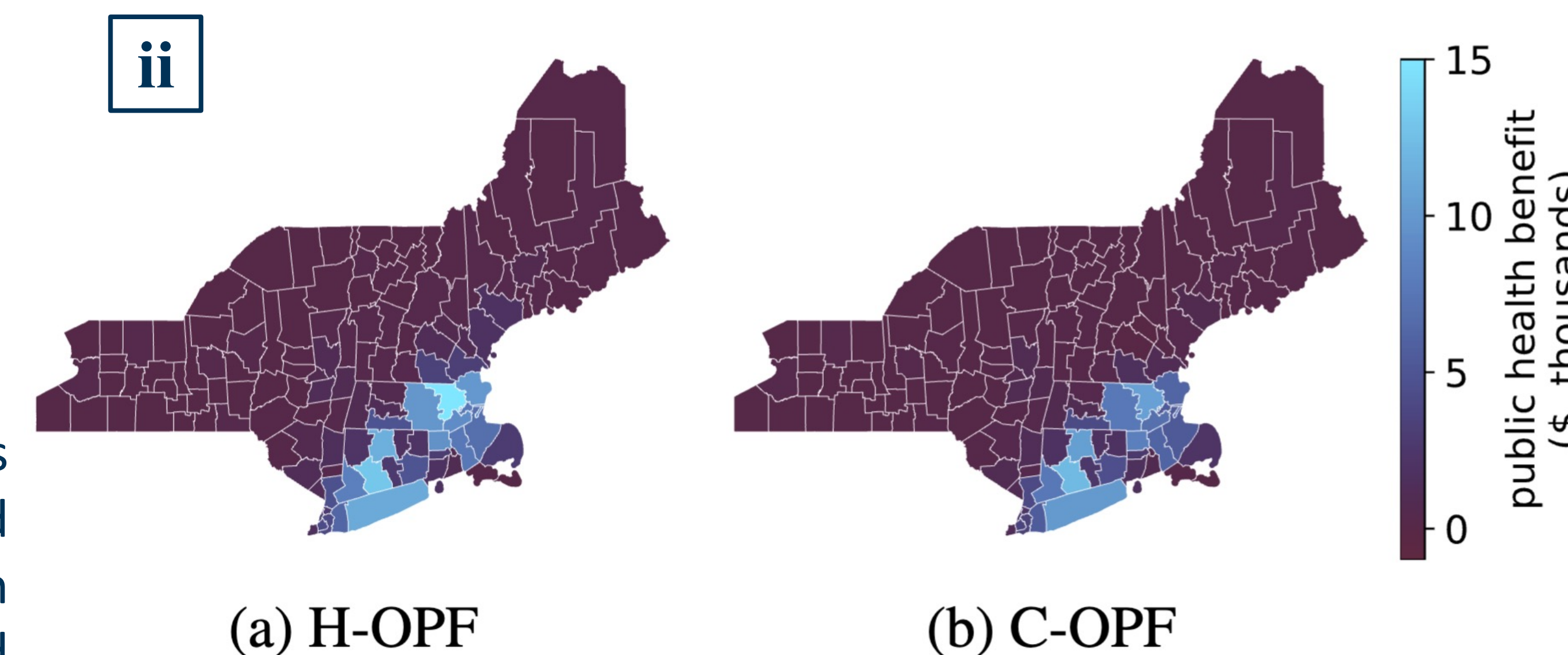
Analyzing Equity Implications
Every model comes with tradeoffs – we found no net decrease in public health by running our model on this specific test grid, but more testing is needed to see if this result is replicated in other areas, and to what degree.

3.3: Results

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	health	carbon	economic	mix
health ($M/hr)	1.56	1.62	1.80	1.56
carbon ($/hr)	737,448	706,880	973,046	727,220
economic ($/hr)	553,840	555,709	535,549	553,524

iii. Resulting health, carbon, and economic costs per hour under each optimization objective. We find that minimizing public health impact correlates with a decrease in carbon emissions

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