Poster: Data-driven Decarbonization of Residential Heating Systems: An Equity Perspective

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ABSTRACT

Since heating buildings using natural gas, propane and oil makes up a significant proportion of the aggregate carbon emissions every year, there is a strong interest in decarbonizing residential heating systems using new technologies such as electric heat pumps. In this poster, we conduct a data-driven optimization study to analyze the potential of replacing gas heating with electric heat pumps to reduce carbon emissions in a city-wide distribution grid. We seek to not only reduce the carbon footprint of residential heating, but also show how to do so equitably. Our results show that lower income homes have an energy usage intensity 24% higher than that of high income ones. We propose equity-aware transition strategies that enforce equity and show that such strategies achieve significant levels of CO_2 reduction while reducing the disparity in value of selected homes by 5× compared to a carbon-first approach.

CCS CONCEPTS

• **Information systems** → **Data analytics**; • **Hardware** → **Impact on the environment**; **Energy metering**.

KEYWORDS

Decarbonization, Electric Heat Pump, Optimization, Equity

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1 INTRODUCTION

Residential energy usage contributes nearly 20% of all greenhouse gas emissions in the United States [4]. Heating and cooling alone account for roughly 38% of these emissions [7]. As the energy system begins a transition towards a carbon-free future in an attempt to avert the disastrous effects of climate change, the building sector will play a major role in this decarbonization.

Decarbonization strategies that simply choose larger homes, by virtue of their higher carbon footprint, might perpetuate social inequity against lower income households. First, such households will not benefit from the efficiencies offered by newer heating technologies. Second, since gas customers indirectly pay for the cost of maintaining the utility's gas-based infrastructure (through their monthly bills), customers who delay their transition are left to bear the higher costs—as the number of gas customers dwindles over time, a shrinking customer base will end up with a disproportionate share of these costs.

2 BACKGROUND

Heating using fossil fuels such as natural gas, propane and oil accounts for more than 47% of all heating energy consumption in United States [1]. In order to meet our carbon reduction goals, replacing gas heating with energy-efficient electric heat pumps has been proposed as an important step towards decarbonization of the future grid [2, 3, 5, 6, 8].

Electric heat pumps are a new and energy-efficient alternative to gas furnace heating during cold seasons, as well as space cooling during summer seasons. During winter seasons, heat pumps pull warm air from outside and concentrate it into your home space, making the inside warm. The reverse is true during summer seasons. Since the main principle behind heat pump operation is heat transfer instead of heat generation, heat pumps are more energy efficient than fossil fuel based burners.

In addition to increased energy efficiency, heat pumps also have other advantages over natural gas. Since they use electricity, as more electricity is sourced from renewable sources, their carbon footprint is generally lower than that of natural gas. Moreover, due to their reduced energy usage, heat pumps can reduce the cost of heating a home by up to 60%. This makes them an attractive source of heating from a carbon, energy efficiency and cost perspective.

3 NEED FOR EQUITABLE TRANSITION

Traditionally, disadvantaged parts of the society have borne the higher burden of pollution, lack of access to clean and renewable energy and higher energy costs. This marginalization has continued even in the energy transition happening today, where less privileged communities are left out of opportunities that facilitate the transition towards a carbon-free future. Therefore, as we move towards decarbonization of the grid, it is important to not only maximize carbon reduction, but also consider how to do so *equitably*.

To study this problem, we leverage a rich real world dataset consisting of gas and electric usage data collected from 4,729 homes in the North East region of the United States. We begin by analyzing how income level impacts energy usage at the household level. We focus on gas energy usage and compute the energy use intensity (EUI) for each home in the dataset.

Figure 1 depicts the average EUI and house value broken down into different income groups. The figure indicates that the average

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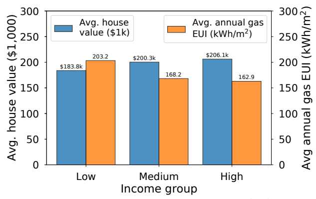


Figure 1: (i) Average house value, and (ii) Average EUI across homes in different income groups.

EUI in low income homes is 202.3, while high income homes have an average EUI of 162.9. This reveals a huge disparity in EUI by income — i.e., EUI in low income homes is 24% higher than that of high income homes, which translates to higher energy cost per unit area for these households. We hypothesize that the root cause of this disparity is the fact that lower income homes may have poor house insulation which results in higher energy losses.

4 DATA-DRIVEN DECARBONIZATION

Here, we present our data-driven decarbonization approach. Our primary goal is twofold — first, to maximize the amount of carbon reduction achieved by transitioning a subset of homes from gas to electric heat pumps, and second, to enable selection criteria that ensure equity in such transition.

Carbon-first Transition. To maximize carbon reduction, we adopt a greedy approach i.e. we order homes by their carbon emission and transition the highest emitters first. Formally, this approach can be formulated as

$$\min \sum_{i=1}^{n} (1 - \alpha_i) \cdot x_i + \alpha_i \cdot y_i \tag{1}$$

where x_i denotes the total gas emission from home i, y_i denotes the total emission from home i after transitioning to electric heat pump heating, and α_i denotes a binary variable which indicates whether or not a home is selected for transition.

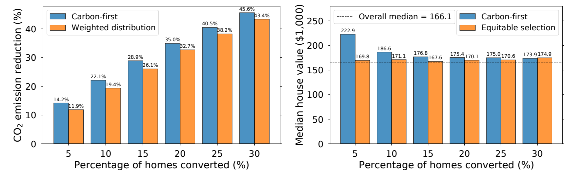
The result of this optimization model is a list of t homes in order of emission reduction priority i.e. to maximize carbon reduction, the highest emitting t homes are selected. To enforce metrics such as equity and targeted transition, we apply the following post-processing sampling strategies.

Equitable Distribution Across Income Groups. The goal of this strategy is to select an equitable number of homes from each income group. To enforce this strategy, we select a proportionate number of homes from each census block according to the total number of homes present in that income group.

Equitable Distribution Across Census Blocks. The goal of this strategy is to select an equitable number of homes from each census block, i.e., to enforce this strategy, we select homes from each block as a proportion of the total homes present in that block.

5 RESULTS

We now analyze the outcome of the transition strategies evaluated in terms of carbon reduction and equity outcomes. Figure 2a depicts the CO_2 reduction achieved from the carbon-first and the equitable census block strategy. The figure shows a reduction in the total CO_2 reduction in the equitable strategy compared to the carbon-first approach e.g. at 5% transition, there's a 2.3% deficit in CO_2 reduction between the two strategies. This is because instead of



(a) (b)

Figure 2: (2a) Carbon emission reduction at varying levels of transition, and (2b) Median house value in each subset selected at varying levels of transition.

targeting high emitting homes only, this strategy also considers lower emitting homes that are in lower represented census blocks, which ensures equity in representation across census blocks.

Next, to study the characteristics of buildings selected by each technique, we analyze the value of homes in each selected subset. Figure 2b depicts the median house value for homes in each subset per strategy. The figure shows that the carbon-first approach is disproportionately skewed towards high value homes. To quantify the disparity, we compute the RMSE between the median value of selected homes and the overall median. The RMSE of carbon-first approach is 25.78, compared to 5.077 in the equitable selection, indicating a reduction of 5× in house value disparity.

6 CONCLUSIONS

In this poster, we conducted a data-driven optimization-based study to analyze the carbon reduction potential of replacing gas heating with electric heat pumps at city scale. Our in-depth analysis into the energy patterns of buildings revealed a huge disparity (24%) between lower and high income households. We proposed equity-aware transition strategies and showed that while their carbon reduction was lower than a carbon-first approach, these equitable strategies achieved significant levels of CO_2 reduction, and at the same time, reduced the disparity in value of selected homes by 5× compared to the carbon-first approach.

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REFERENCES

[1] U.S. Energy Information Administration. 2015. *5 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables.* Retrieved May 23, 2022 from https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce6.1.pdf
[2] Sherri Billimoria, Leia Guccione, Mike Henchen, and Leah Louis-Prescott. 2021. The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings. In *World Scientific Encyclopedia of Climate Change: Case Studies of Climate Risk, Action, and Opportunity Volume 3.* World Scientific, 297–304.
[3] Anna M Brockway and Pierre Delforge. 2018. Emissions reduction potential from electric heat pumps in California homes. *The Electricity Journal* 31, 9 (2018), 44–53.
[4] Benjamin Goldstein, Dimitrios Gounaridis, and Joshua P Newell. 2020. The carbon footprint of household energy use in the United States. *Proceedings of the National Academy of Sciences* 117, 32 (2020), 19122–19130.
[5] A Hopkins, K Takahashi, D Glick, and M Whited. 2018. Decarbonization of Heating Energy Use in California Buildings. *Synapse Energy Economics* (2018).
[6] Noah Kaufman, David Sandalow, Clotilde Rossi Di Schio, and Jake Higdon. 2019. Decarbonizing space heating with air source heat pumps. *Center Glob. Energy Policy* 1 (2019), 1–46.
[7] Jessica Leung. 2018. Decarbonizing US buildings. *Center for Climate and Energy Solutions* (2018).
[8] Hongyu Zhang, Li Zhou, Xiaodan Huang, and Xiliang Zhang. 2019. Decarbonizing a large City's heating system using heat pumps: A case study of Beijing. *Energy* 186 (2019), 115820.