Public review for

Equity-aware Decarbonization of Residential Heating Systems

John Wamburu, Noman Bashir, Emma Grazier, David Irwin, Christine Crago, Prashant Shenoy

Buildings are a major contributor of carbon emissions. The electrification of heating systems, which involves replacing traditional furnaces and air conditioning systems with electric heat pumps, is an effective way to reduce the carbon emissions associated with building operations. To incentivize homeowners to install a heat pump or upgrade their existing system, electric utilities and governments are increasingly offering financial rebates. In this paper, it is argued that a decarbonization strategy that results in the greatest reduction in carbon emissions will not be equitable, because it mostly targets large homes owned by high-income families. To address this important problem, the authors propose multiple equity-aware strategies for offering rebates that maximize carbon reduction while satisfying equity constraints. The strategies are developed using a data-driven optimization approach and evaluated on a real-world dataset of electricity and gas consumption of 4,729 residential buildings in a small city. The finding of this paper could be of interest to policy makers that design the rebate programs, as well as researchers who work on defining new equity measures which can be incorporated in this optimization problem.

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Equity-aware Decarbonization of Residential Heating Systems

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Most buildings still rely on fossil energy — such as oil, coal and natural gas — for heating. This is because they are readily available and have higher heat value than their cleaner counterparts. However, these primary sources of energy are also high pollutants. As the grid moves towards eliminating CO_2 emission, replacing these sources of energy with cleaner alternatives is imperative. Electric heat pumps — an alternative and cleaner heating technology — have been proposed as a viable replacement. In this paper, we conduct a data-driven optimization study to analyze the potential of reducing carbon emission by replacing gas-based heating with electric heat pumps[1]. We do so while enforcing *equity* in such transition. We begin by conducting an in-depth analysis into the energy patterns and demographic profiles of buildings. Our analysis reveals a huge disparity between lower and higher income households. We show that the energy usage intensity for lower income homes is 24% higher than higher income homes. Next, we analyze the potential for carbon emission reduction by transitioning gas-based heating systems to electric heat pumps for an entire city. We then propose equity-aware transition strategies for selecting a subset of customers for heat pump-based retrofits which embed various equity metrics and balances the need to maximize carbon reduction with ensuring equitable outcomes for households. We evaluate their effect on CO_2 emission reduction, showing that such equity-aware carbon emission reduction strategies achieve significant emission reduction while also reducing the disparity in the 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**.

Additional Key Words and Phrases: Equity, Decarbonization, Heat Pumps

1 INTRODUCTION

Residential energy usage is one of the biggest contributors of carbon emissions. For instance, in the U.S., the residential energy sector accounts for 21% of all energy consumption, and is responsible for 20% of the country's aggregate carbon emission [18]. At the same time, a typical U.S. household spends up to \$2,000 in energy bills every year [5] and heating makes a large portion of this expense, accounting for up to 29% of annual energy bills [2]. This makes reducing home energy usage e.g. by replacing heating with a more efficient energy source, the single most effective way to save money and reduce a home's contribution to environmental emissions.

However, upgrading energy efficiency requires significant initial cost that may be prohibitive for lower and middle income households. As a result, such improvements are often accompanied by government rebates to incentivize homeowners to install more energy efficient equipment. To ensure that improvements are seen equitably across the whole society, it is important that demographic factors such as household income be taken into account in transition, and that such rebates are not targeted towards high energy usage homes which would yield the highest CO_2 reduction only.

From a utility's perspective, a decarbonization strategy involves a planned gradual shift of its customers from gas and oil-based heating to electric heat pump-based heating and cooling. This involves determining which customers to choose for heat pump retrofits in order to meet targets for reducing carbon emissions, in line with commitments made at the UN's Paris Climate Agreement [8]. One strategy is for a utility to identify its largest emitting customers — which are homes with the highest heating bills in the winter — and prioritize them for heat pump retrofits. While such a strategy will yield the greatest *initial* reduction in carbon emissions from residential heating, it will not be equitable from a societal perspective. The homes with higher heating bills are likely to be large-sized homes housing affluent residents, resulting in inadvertently benefiting high-income groups. Hence, we should take an *equity* perspective while devising a strategy to reduce carbon emissions of heating systems.

Decarbonization strategies that target bigger homes, due to their high carbon footprint, might perpetuate social inequity against lower income households in multiple ways. First, low income households will not benefit from the high energy efficiencies of newer heating technologies. Second, since gas customers pay for the cost of maintaining the utility's gas network, customers who cannot transition will pay higher costs as the number of gas customers dwindles over time [4]. Finally, high income households are better equipped to bear the capital cost of replacing a heating system without any subsidies. Therefore, the decarbonization studies should ensure that low income households are also able to benefit from and participate in decarbonization efforts. Therefore, an equitable decarbonization framework must not only consider carbon reduction potential but also quantify how socially equitable decarbonization strategies are. Recently, multiple cities have begun to factor in the social equity in their decarbonization policies by informing the distribution of decarbonization investments such as financial rebates [14, 34, 36].

In this paper, we conduct a multi-step data-driven optimization-based study to analyze the decarbonization potential of replacing gas heating with electric heat pumps in a city-wide distribution grid while focusing on *equity*. Our work is based on real-world gas-based heating data from 4,729 residential buildings gathered at hourly granularity over a 1-year period. We first analyze the heating demand of buildings and quantify their carbon footprint. Next, we analyze the Energy Usage Intensity (EUI) of buildings alongside the corresponding demographic profiles revealing a huge disparity between higher and lower value homes, and show how a transition strategy that prioritizes carbon emissions only perpetuates such disparity. We then propose an *equity-aware* carbon-reduction approach that incorporates both the carbon reduction and social equity goals into the transition strategy. In conducting our empirical analysis and designing our equity-aware decarbonization algorithms, this paper makes the following contributions.

Energy demand and demographic patterns. We conduct a data-driven analysis to demonstrate the need for an equitable decarbonization strategy for transitioning homes away from gas-based

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[1] A preliminary version of this work appeared as a 2-page poster at ACM e-Energy'22.

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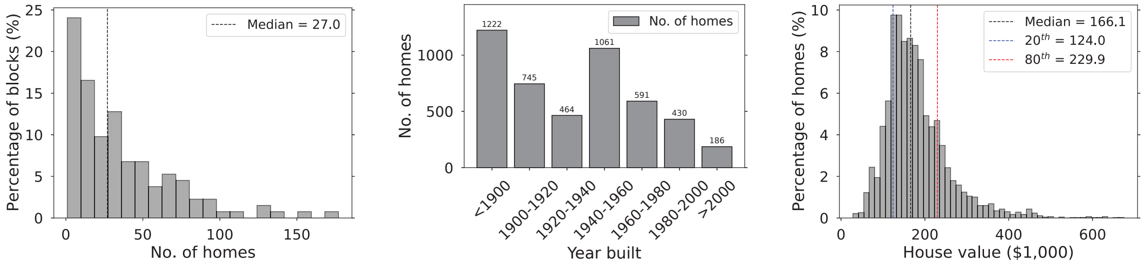

(a) Homes per Census Block (b) Homes by Age (c) Values of Homes

Fig. 1. *Distribution of number of homes per census block (a), number of homes by age (b), and values of homes (c).*

heating. We analyze the heating energy demand of buildings to quantify Energy Usage Intensity (EUI) and carbon footprint of buildings. We observe that the lower income homes have a higher EUI and incur a higher energy cost per unit area than higher income homes. This disparity extends along racial lines and the neighborhoods occupied by predominately non-white races are disproportionately affected. Finally, we show that EUI increases as buildings age, indicating an opportunity to target old homes in the transition.

Decarbonization benefits of electric heat pumps. We analyze the energy usage reduction and decarbonization potential of transitioning gas-based heating systems to electric heat pumps. Our results indicate that such transition allows an average home to cut energy usage by up to 60% and reduce carbon emissions by up to 80%. At city-scale, carbon emissions can be reduced by ≈55% by transitioning 40% of homes from gas to heat pumps. We also demonstrate that a carbon-first approach perpetuates social inequity by preferring higher value homes first in gas-to-electric transition.

Equity-aware optimization for decarbonization We enable equity-aware selection a subset of customers for heat pump retrofits. Our selection embeds equity metrics into a carbon-first optimization technique and enables a flexible approach that balances the need to maximize carbon reductions while also ensuring equitable outcomes for residential households. We present both equity-aware and targeted policies to determine an overall decarbonization strategy. Our results show that these equitable strategies achieve significant carbon emission reduction in transition to electric heat pumps while reducing the disparity in the value of selected homes by 5× compared to a carbon-first approach. We release the source code for our transition strategy as an open source tool[2] with sample datasets.

2 BACKGROUND

In this section, we present background on the decarbonization benefits of electric heat pumps, the impact of demographic factors on energy usage, and equity in the energy transition.

2.1 Decarbonization benefits of electric heat pumps

Electric heat pumps have recently become popular as a viable and cleaner replacement for high polluting energy sources such as natural gas, oil and coal. To heat a building, heat pumps move heat from the outdoors into the interior to warm the building. To cool a building, they operate in the reverse order by moving hot air from the interior into the exterior. Because of transferring instead of generating heat, electric heat pumps are significantly more energy efficient than primary energy sources. When deployed in a home, they can reduce the cost of heating by up to 60% [3]. This is especially beneficial to low income households as it lowers their overall cost of energy. In addition to energy efficiency, electric heat pumps also leave a lower carbon footprint compared to other heating energy sources. Since they are powered by electricity, their carbon footprint is based on the energy mix used to power the electric grid. As the share of renewable energy continues to increase in the grid, electric heat pumps have the potential to further lower their aggregate CO_2 footprint. Because of these benefits, multiple studies have proposed heat pumps as a crucial heating replacement [12, 13, 20, 24, 40].

Despite the energy efficiency and carbon benefits of electric heat pumps, their widespread adoption is yet to be realized. The initial cost of installation as well as the duration of payback time discourage homeowners from adopting heat pump technology [37]. Further, since their heating performance degrades as the temperature decreases, most homeowners in very cold climates are reluctant to adopt them. However, as heat pump technology improves, their performance in cold climates will improve leading to higher adoption.

2.2 Impact of demographic factors on energy usage

Socio-demographic factors such as income, house size, employment status etc., affect energy usage patterns at the household level. For example, household income and home size are typically positively related to residential energy consumption i.e. higher household income often leads to higher energy usage [17]. Therefore, to implement an efficient energy transition, understanding these factors and how they affect energy usage as well as the ability of a household to adopt new technology such as migrating to heat pumps is essential. This paper analyzes demographic patterns of a city and shows how these patterns can be used to design optimal policy for transition.

2.3 Equity in the energy transition

Equity in energy usage is measured using three main concepts [22, 26]. First, *distributional equity* ensures that the burdens and benefits of the energy transition are accrued equitably across populations, i.e., some segments of the population do not disproportionately share the burdens, while other segments enjoy the benefits. Second, *procedural equity* ensures that the public engagement processes for planning and implementing the energy transition are conducted in a diverse and inclusive manner. Finally, *recognition equity* ensures that historical injustices against certain demographics are acknowledged, and conscious efforts to remedy such inequalities are made. Our work focuses on distributional equity. As decarbonization is achieved by transitioning from natural gas heating to electric heat pumps, our goal is to ensure that the benefits of such transition are distributed equitably across the whole population.

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[2] https://github.com/umassos/equity-aware-decarbonization

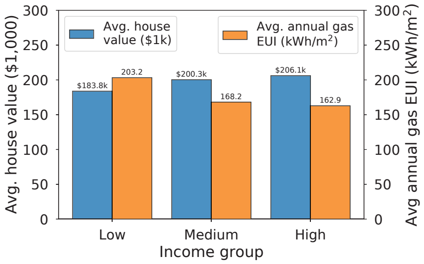


Fig. 2. *Average house value and annual gas energy usage intensity across homes in different income groups.*

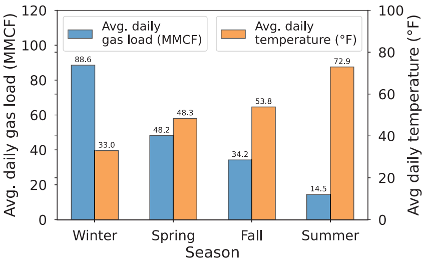


Fig. 3. *Aggregate gas demand and temperature variation across seasons.*

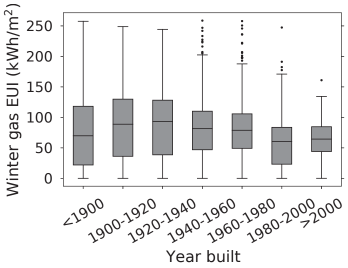


Fig. 4. *Distribution of EUI by age of building i.e. year the building was built.*

To accurately measure energy equity of decarbonization strategies requires identifying suitable equity metrics. Energy Use Intensity (EUI) measures the energy consumption per unit area and has been used widely to measure disparity in energy usage across different demographic profiles, e.g., high versus low income households [11, 32, 38]. In this paper, we use EUI to examine disparity between low and high income households. However, comparing high versus low EUI has its challenges. For example, larger homes may be considered more "efficient" if they have lower EUI while in fact, they may have a higher energy consumption compared to smaller homes. Since house value is correlated with income, our goal is to ensure equity across low- and high-income homes by reducing the disparity in EUI between high- and low-value homes.

3 A CASE FOR EQUITABLE ENERGY TRANSITION

Data-driven techniques that leverage building and energy data to facilitate the energy transition have recently become an active research area. For instance, researchers have proposed several techniques that use data-driven analysis and machine learning techniques to identify energy inefficiencies in buildings and recommend areas of improvement [9, 21]. However, most of the studies focus only on identifying energy usage patterns without contextualizing the underlying demographic and societal causes of such observations. As a result, these studies lack an *equity* perspective.

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 strive for the decarbonization of the grid, it is important to not only focus on carbon reduction, but also consider how to do so *equitably.* A prerequisite for designing equitable techniques is that we must understand the underlying inequity that exists in energy usage.

To quantify the social inequity in energy usage patterns across different demographic profiles, we leverage two main datasets which we describe in more detail in Section 3.1. First, we use fine grained energy usage data to discover patterns in energy usage at the household level. Second, we combine the observed patterns with demographic and tax data at the community level to discover how energy usage correlates with social and demographic constructs. We show how different demographic profiles, including income level, value of a home, age of a home, and race of the residents, impact energy usage patterns. We also show how such insights can help devise equitable energy transition and decarbonization strategies.

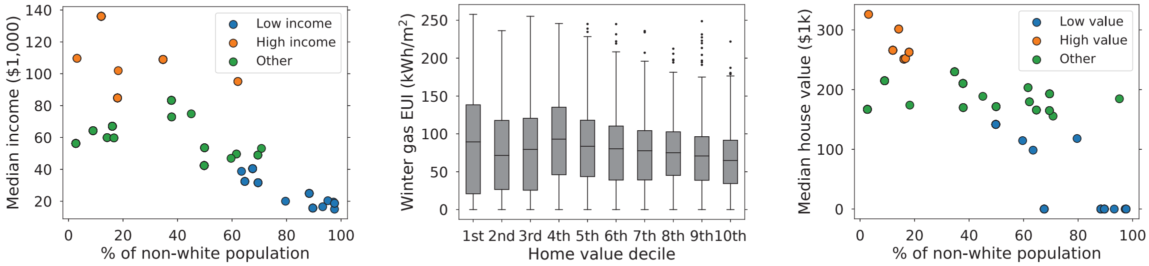
3.1 Datasets

3.1.1 Gas distribution and usage dataset. Our energy usage dataset consists of electric usage (in kWh) and gas usage (in CCf) data recorded from 14,094 buildings in a small city. The dataset also contains real estate information that includes a building's size, type of home e.g. single vs multi-family, type of building e.g. apartment, school etc, and the year the building was built. Since our analysis is primarily based on residential transition, we filter out apartments, factories, schools, etc — whose reported size may be inaccurate — and perform our data-driven analysis on 4,729 single family residential buildings. The entirety of usage data spans 2014 to 2019. However, our study focuses on the one year period between Jan-Dec 2019, which is enough to draw our conclusions from.

Figure 1a depicts the distribution of the number of homes in each census block. The figure shows a long tail. Most blocks have between 1-15 homes, median block has 27 homes, and the most populated block has more than 150 homes. These characteristics present interesting opportunities for equitable and targeted transition. For example, a targeted transition strategy may focus on homes in the same block to minimize disruptions to the gas network. Similarly, an equitable transition strategy may aim to select an equal number of homes from each block to ensure equity across the population. Figure 1b depicts the number of homes by the year built. Most homes are old and built in the 19^{th} century. This presents an opportunity for targeted transition where older buildings are prioritized. Such transition can improve safety by retiring older gas lines that were installed in the 19^{th} century. Figure 1c depicts the distribution of house value in the city. The figure shows the median house value is $\approx \$165,000$, with a few homes having a value above $\$600,000$.

Figure 3 depicts the gas demand and temperature variation across seasons. The figure shows an inverse relationship between temperature and gas demand — as the temperature falls, gas consumption rises due to increased heating demand in homes. The figure also shows that the average daily gas demand during winter months is 88.6MMCF, which is 6× the daily average demand during summer (14.6MMCF). Since winter usage is primarily driven by heating demand, this reveals significant potential to reduce gas consumption by transitioning from gas to electricity.

3.1.2 Demographic profile data. We use Geocode API [1] to collect demographic data such as race, population and median income. Our analysis uses the most recently available per-block census data for the year 2020. Our gas distribution dataset also contains the address of each home. We use geocoding to map each address to a parent census block, which we then use to compute our equity metrics.



(a) Household Income by Race
(b) EUI by House Value
(c) House Value by Race

Fig. 5. *Distributions of household income by race (a), distribution of EUI by house value (b), and distribution of house value by race (c).*

3.2 EUI and demographic analysis

We first analyze the impact of income on the household energy usage. We focus on gas energy usage and compute the energy use intensity (EUI) for each home. We convert gas usage data (in volume consumed per unit time in CCF) to the equivalent electricity usage in kWh. To do so, we compute the amount of heat energy generated from gas heating, and then compute the electric energy required to generate the same amount of heat energy. We then use census data to group homes according to household income relative to the whole population. We classify homes with income <20*th* percentile, 20-80*th* percentile, and >80*th* percentile as the *low, medium,* and *high* income homes. Our subsequent analysis of EUI and house values uses the resulting income groups.

Figure 2 depicts the average EUI and house value for each income group. The average EUI for high income homes is 162.9, while low income homes have a 24% higher average EUI of 202.3. This highlights a large disparity in EUI by income and reveals that low income homes cost more per unit area to heat than high income homes. We hypothesize that this disparity is because lower income homes tend to have poor house insulation, which results in less energy-efficient heating and high energy usage per unit area. Finally, our analysis also indicates that homes in the high income group are 12% higher in value than homes in the low income group, but are less expensive to heat than their low-income counterparts.

We next examine the racial distribution of population in each income group. To do so, we use the racial distribution for each census block and compute the ratio of white to non-white population. Figure 5a, demonstrates that the lower income census blocks are predominantly made up of non-white populations, while the wealthiest blocks are predominantly white, indicating society's racial disparities. The lower income group, which is largely non-white population, experiences the highest energy cost burden. To examine the impact of house value on the resulting EUI of the home, we group homes into deciles based on the individual home value. Figure 5b depicts the distribution of EUI for homes in each decile. It indicates that lower value homes have higher EUI than higher values homes. The lowest 10% of homes have an average EUI of 90.8, compared to an average EUI of 66.8 for top 10% of homes. An EUI disparity of 36% means that lower value homes have a higher energy cost per unit area further exacerbating the inequity between groups. The examination of racial profiles based on home values reveals racial inequity in energy usage. Figure 5c depicts the relationship between the value of a home and the racial distribution of residents. The lower value homes are predominantly located in areas with a high percentage of non-white residents, while the most expensive homes are primarily located in areas with a high percentage of white residents.

Finally, to examine the impact of age on the EUI of a home, we first group homes based on the year the building was built (buckets of 20 years each). Figure 4 depicts distribution of EUI for all homes in each age group. The figure shows that the older homes have a higher EUI compared to newer homes. This is because the building envelope degrades over time, the building becomes less energy efficient, and the EUI increases. Further, newer buildings are subject to higher building standards and are fitted with newer and more efficient appliances. This reveals an important insight for designing decarbonization strategies and for energy policy. Newer buildings are already less carbon-intensive and older homes should be prioritized in energy transition and decarbonization efforts.

Summary and Key Takeaways. Our data-driven analysis yields the following key observations.

1. Low income homes have higher EUI than high income homes. They pay a higher energy cost per unit area despite having lower purchasing power than high income homes and share a disproportionate energy cost burden.
2. Income based inequity disproportionately affects non-white populations as they are more likely to be low-income earners than white populations. This also means that energy inequity also affects non-white population more than white population.
3. Lower value homes have higher EUI than high value homes. They pay a higher energy cost per unit area than their high value counterparts. Since non-white populations are more likely to live in lower value homes, house value inequity also affects non-white populations more than white populations.
4. Older homes have a higher EUI than newer homes. This presents an opportunity for targeted transition based on the home age.

Given these observations, the primary goal of our paper is to devise a decarbonization strategy to transition homes from gas-based heating to electric heat pumps that achieves highest carbon reductions while satisfying *equity* constraints. Specifically, we seek to answer the following research questions.

1. How can we design an optimization framework that maximizes carbon reduction by transitioning a subset of homes from a group from gas-based heating to electric heat pumps?
2. How can we embed *equity* metrics into a framework for maximizing carbon reductions to ensure *equitable* transition?
3. How do the carbon-first and *equity-aware* approaches impact carbon emissions? What is the impact of level of transition on the carbon footprint and energy usage intensity of homes?

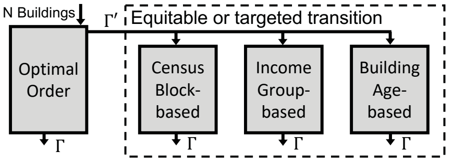


Fig. 6. Two Step Decarbonization Approach.

4 DATA-DRIVEN DECARBONIZATION

In this section, we present our data-driven decarbonization approach. Our primary goal is twofold — first, to maximize the amount of carbon reduction while transitioning a subset of homes from gas-based heating to electric heat pumps, and second, to enable selection criteria to either ensure equity or targeted selection of homes for transition. An *equitable* transition reduces disparity across different demographic profiles in a chosen metric, e.g. value of selected homes. A targeted transition may refer to selecting a group of homes that meet certain criteria, e.g. homes built in a given time period to retire old gas lines. As shown in Figure 6, our data-driven approach is therefore a two-step process. First, we cast an optimization problem with the objective of maximizing total carbon reduction by selecting the highest emitting homes. Second, we embed additional constraints to ensure *equity* in home selection or target specific homes that meet specified criteria such as age and location.

4.1 Step 1: Carbon reduction optimization

In this step, we develop a linear optimization model whose goal is to maximize the amount of carbon reduction achieved while transitioning homes from gas-based heating to electric heat pumps.

Let $H = \{h_1, h_2 ... h_n\}$ denote the set of buildings, each indexed by i. Let X_i^g denote the total carbon emissions from the cumulative annual gas consumption for heating for building i. Let X_i^e denote the total carbon emissions from the cumulative annual electricity consumption of heat pumps for building i. Let τ_i be a binary variable that represents the status of transition for the building i and Γ denotes the target number of buildings for transition. Our objective is to select Γ buildings from the set H that result in the highest carbon emissions reductions after transitioning from gas-based heating to electric heat pumps. This objective can be described as follows.

$$\begin{aligned} \min \quad & \sum_{i=1}^{n} (1-\alpha_i)\cdot X_i^g + \tau_i \cdot X_i^e \\ \text{s.t.,} \quad & \text{Equations (2) - (3)} \\ \text{vars.,} \quad & X_i^g, X_i^e, \tau_i, \Gamma \quad \forall i \end{aligned} \tag{1}$$

To ensure that only Γ buildings are transitioned, the sum of all values of τ_i must equal Γ, as stated below.

$$\sum_{i=1}^{n} \tau_i = \Gamma \tag{2}$$

We next ensure that a building cannot have negative carbon emissions from either the gas consumption or the electric demand.

$$X_i^g \geq 0, X_i^e \geq 0 \quad \forall i \tag{3}$$

The emissions from gas, X_i^g, for a building i is a multiple of the total heating gas demand Y_i^g and the carbon intensity of gas I_g. Similarly, X_i^e, is a multiple of the total electricity demand Y_i^e and the carbon intensity of the electric grid I_e.

$$X_i^g = Y_i^g \times I_g, \quad X_i^e = Y_i^e \times I_e \tag{4}$$

4.2 Step 2: Equitable or targeted transition

The goal of our transition strategies, equitable or targeted, is to select an equitable distribution of homes across income groups, census blocks or building age. To ensure that there are enough homes to pick across each group in Step 2, we set $\Gamma = \Gamma'$ — i.e. the target number of homes in Step 1 — higher than the actual target Γ. In our experiments, we set $\Gamma' = \Gamma \times N$, where $N > 1$ to selects the top $\Gamma \times N$ emitting homes. We then apply our equitable or targeted sampling strategy to select $\Gamma' \div N$ homes, which is the actual expected number of homes. We start with $N = 2$ and increase the value of N until we get sufficient number of homes for all groups. For our dataset, $N = 3$ yields sufficient homes for all strategies and we use this constant value of N in all the experiments. We describe these strategies next.

4.2.1 *Equitable transition.*

To ensure equitable distribution of selected homes, we analyze two strategies that ensure an equitable distribution across income groups or census blocks.

Equitable distribution across income groups. The goal of this strategy is to select an equitable number of homes from each income group as the homes selected for transition. We do this to eliminate over-representation from any of the three income groups discussed in Section 3. To select the subset $\Gamma' \div 3$ from Γ', we first compute Γ_{low}, Γ_{medium} and Γ_{high}, where $\Gamma_{low} = \frac{\text{no. of low income homes}}{n} \times \Gamma$, $\Gamma_{medium} = \frac{\text{no. of medium income homes}}{n} \times \Gamma$, and $\Gamma_{high} = \frac{\text{no. of high income homes}}{n} \times \Gamma$. We then select Γ_{low} low income homes from Γ', Γ_{medium} medium income homes from Γ', and Γ_{high} high income homes from Γ'. The final number of homes $\Gamma = \Gamma_{low} + \Gamma_{medium} + \Gamma_{high}$, and is made up of an equal proportion of homes from each income group in the subset.

Equitable distribution across census blocks. The goal of this strategy is to select an equitable number of homes for transition from each census block, i.e., we select homes from each block as a proportion of the total homes present in that block. We select the target number of homes Γ from Γ' as follows. We first compute Γ_b for each block, where $\Gamma_b = \frac{\text{no. of homes in block}}{n} \times \Gamma$ for all blocks. We then select Γ_b homes from Γ' for each block. The final number of homes $\Gamma = \Gamma_{b1} + \Gamma_{b2} + ... + \Gamma_{bk}$, where k is the total number of blocks, and is made up of an equal proportion of homes from each block as a fraction of the total number of homes in that block.

Skewed transition. In addition to equal selection across income groups and census blocks, we also evaluate the impact of skewed transition towards certain demographics i.e. towards low and high income groups. To skew transition towards low income households, we select half of all transitioned homes from the low income group (i.e. 50%), and 25% from middle and high income homes respectively. This strategy can be used to enforce affirmative action policies. Similarly, to skew transition towards high income homes, we select 50% of all transitioned homes from the high income group, and 25% from low and middle homes. We then analyze the impact of skewed transition on home value and CO_2 reduction post transition.

4.2.2 *Targeted transition.*

We next analyze strategies that provide targeted transition for homes that meet a specific criteria. Targeted transition from gas can improve the safety of the infrastructure and reduce the cost of transition. For example, older homes can be prioritized because they are typically serviced by older gas lines that

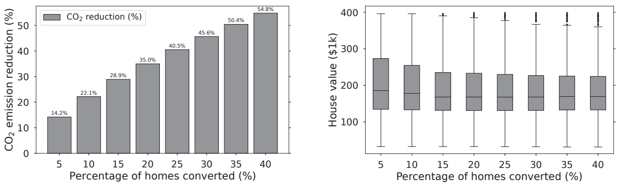


Fig. 7. *Carbon emission reduction at varying levels of transition (left), and median house value for homes selected at varying levels of transition (right).*

may pose risks of leakage. To transition such homes, targeted strategies can first select homes built within a particular decade while also maximizing carbon reduction. Similarly, a targeted strategy can select homes in a certain geographic location that are serviced by the same gas line to retire an old or leaky gas line. We analyze two targeted transition strategies that maximize carbon reduction while prioritizing homes based on age and geographic location.

Age-based selection. In this strategy, we skew the selection towards homes within a particular age group. This strategy allows targeting homes that have higher carbon footprint due to their age. Our analysis in Section 3 showed that homes built between 1920-1960 years have a disproportionately high EUI compared to homes built later. We can prioritize homes in these age groups in our transition criteria. We select a subset Γ as follows. First, we prioritize homes within Γ' whose age group falls in the selected targets. If the number of homes in the targeted age group is less than Γ, we select the remainder of homes from Γ' in order of carbon emissions. The result is a subset of homes that maximizes carbon emissions reduction and falls within the specified age group.

Block-based selection. Our next strategy targets homes based on census blocks and offers two main advantages. First, since the transition from gas will involve migrating customers from existing gas lines, targeting a group of homes that get served by the same gas line lowers the cost of transition from a gas utility's perspective. If all homes on a certain line are migrated, maintenance costs on that line will be eliminated, and the line can be shut off from supply. This strategy can also be used to target old lines which would otherwise need to be replaced or upgraded. Second, neighborhoods with high aggregate carbon footprint can be targeted to maximize carbon reduction by transitioning all homes within such blocks.

To perform targeted transition by blocks, we skew selection towards certain blocks by selecting all homes within that block for transition. We first compute the aggregate carbon footprint for each block that exists in the selected Γ' homes. We then compute the total number of homes in each block Γ_b. If Γ_b is less than the required target Γ, we select all homes in that block, and eliminate homes in Γ' that do not fall in the specified blocks.

5 EXPERIMENTAL EVALUATION

In this section, we evaluate the performance of our carbon-first approach, as well equitable and targeted strategies on carbon reduction. We evaluate different levels of transition i.e. from 5-40%. At each transition level, we compute the overall carbon reduction, as well as analyze the EUI and value of homes in the selected subset. We then conduct equity-aware analysis to evaluate the transition from an equity and a targeted perspective. We have released the source code with sample data as an **open source tool** for **reproducibility**.

5.1 Experimental setup

The gas and electric data consists of usage data recorded at hourly and five-minute granularity respectively. Our analysis computes the total CO$_2$ emitted from the gas use, and estimates the potential savings post transition. We begin by performing load disaggregation on the gas usage data i.e. we split total consumption into the constituent heating and appliance loads. To do so, we compute the average daily usage during summer months, and subtract this value from the annual gas load. Our hypothesis here is that the average consumption during summer is predominantly made up of appliance usage, and all consumption above this threshold mainly goes to heating. Next, we account for the inherent energy loss of gas furnaces. We assume a gas furnace is 87.5% efficient, which is the midpoint between high and standard efficiency furnaces. Finally, we use the emission factor of gas to compute the total emission from the gas load for each building i.e. 0.0551 MT/MCF [7].

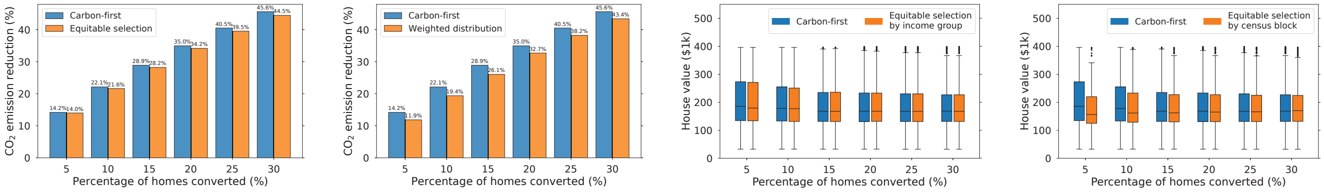
Next, we compute the expected CO$_2$ emission from generating an equivalent amount of heat energy as a gas furnace using an electric heat pump. We first convert heat energy to the corresponding electric energy. To do so, we use a Heating Seasonal Performance Factor (HSPF) of 8.5, which is typical of many efficient heat pump models. Note that CO$_2$ emission from using electric energy comes from the electricity generation process. Therefore, to estimate CO$_2$ emision from electric heat pumps, we use the CO$_2$ emission factor of the U.S. electric grid i.e. 0.000386 MT CO$_2$/kWh [19, 35].

5.2 Carbon-first transition

We begin by analyzing the effect of transitioning homes from gas to electric heat pumps using the carbon-first approach. To do so, we simulate electric heat pump transition by converting emission from transitioned homes from gas to electric heat pump emissions. We first run our carbon-first framework on the data while varying the target number of homes from 5-40%. At each transition level, we compute the total amount of carbon emissions reduced as well analyze the effect on EUI after such transition.

Figure 7 (left) depicts the total carbon reduction achieved by transitioning a varying number of homes using the carbon first approach. The figure shows a linear relationship between the amount of carbon reduction achieved and the number of transitioned homes. For example, transitioning 5% of homes from gas to electric heat pump results in a 14.2% reduction in total emissions. At the other end, replacing 40% of gas-based heating results in a 54.8% reduction in carbon emission. This is because the carbon intensity of electricity in our area of study is lower than the carbon intensity of the natural gas, and the amount of energy required by electric heat pumps to generate heat is also lower than what is required by gas.

We next examine the value of homes selected by the carbon-first approach. Figure 7 (right) depicts the median house value for homes selected at the various levels of transition. The figure shows an inverse relationship between the number of homes transitioned and the median value of homes in the subset. At low transition levels, the median house value is high, indicating this approach prefers higher value houses to lower value ones. This indicates bias against lower value homes in selection and perpetuates inequity.



(a) Income Group Emissions (b) Census Block Emissions (c) Income Group House Values (d) Census Block House Values

Fig. 8. *Carbon emissions achieved for decarbonization strategy that targets equity based on income group (a) and census block (b). House values for homes selected based on approaches that target equity based on income group (c) and census block (d).*

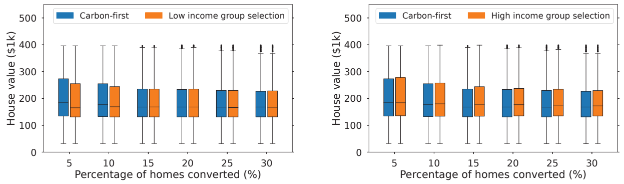


Fig. 10. *Home value in skewed transition towards low income homes (left), and Home value in skewed transition towards high income homes (right).*

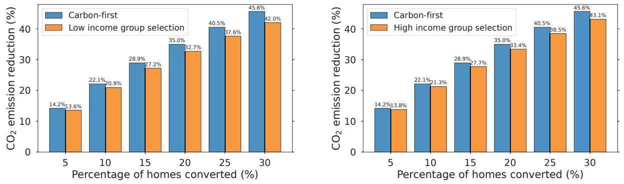


Fig. 9. *CO_2 reduction in skewed transition towards low income homes (left), and CO_2 reduction in skewed transition towards high income homes (right).*

5.3 Equitable transition

We next analyze the impact of equity-aware transition strategies. We apply the equitable transition approaches from Section 4.2 and analyze the reduction in carbon emissions, as well as the demographic properties of selected homes. Since these approaches focus on optimizing the trade-off between carbon reduction and equity, the overall amount of emission reduction is lower than the carbon-first approach. However, disparity in energy usage across different groups is minimized. We analyze the performance of equitable transition by income groups and geographical location i.e. census blocks.

Figure 8a depicts the results for a strategy that targets equity based on income groups. The figure shows a slight reduction in the total amount of carbon reduction achieved compared to the carbon-first approach. Carbon emissions reduction decrease by 0.2% from 14.2 to 14% at 5% transition, and by 1.1% from 45.6 to 44.5% at 30% transition. This is because some homes that have lower emissions are being added to the subset while some high emitting homes are removed to ensure equity in the selection process. However, the figure still indicates a super-linear relationship between the number of homes converted and the amount of carbon reduction achieved.

Since census blocks share similar demographic characteristics, as discussed in in Section 3, equalizing the number of selected homes from each blocks ensures an equitable selection across different demographic profiles. Figure 8b depicts the carbon emission reductions for a strategy that targets equity across census blocks. As expected, the amount of carbon emissions reduction decrease compared to the carbon-first approach—by 2.3% from 14.2% to 11.9% at 5% transition. This is because this strategy considers lower emitting homes that are in under-represented census blocks in carbon-first approach, which ensures equity in representation across census blocks.

Next, we quantify disparity by analyzing the value of homes for equity-aware technique. Figure 8c depicts the median house value at various transition levels for the equitable income group strategy. The figure shows an equitable distribution of house value as the median house value in each subset is closer to the overall median. We use the median because the distribution of house value is long-tailed (as shown in Figure 1c), and using the mean would skew towards higher value homes. Figure 8d depicts the median house value for a strategy that targets equitable distribution by census block. It shows an equitable selection, based on house value, as the median value in each group being closer to the overall median compared to the carbon-first approach. To quantify the reduction in disparity, we compute the RMSE between the median value of selected homes and the overall median. We chose this metric to capture the difference between selected homes and the overall expectation. For each transition level, we compute the deviation between the median value of selected homes and the global median. We then compute the RMSE across all transition levels. The RMSE in median house values in the carbon-first approach and equitable selection by block are 25.78 and 5.08, respectively, indicating a 5× reduction.

5.4 Impact of skewed transition

Our skewed transition strategies can be used to enforce affirmative actions. In such strategies, preference is given to historically marginalized groups. To evaluate the impact of such strategies, we skew transition towards low income households and analyze the impact on CO_2 reduction and selected home value. We also present a transition strategy that skews towards high income homes.

Figure 9 depicts the impact of skewed transition on CO_2 reduction. Figure 9 (left) depicts the results of skewing transition towards low income homes. The figure shows decrease in CO_2 reduction compared to the optimal approach. For example, at 5% transition, CO_2 reduction decreases by 0.6% and by 3.6% at 30% transition. Figure 9 (right) depicts the results of skewing transition towards high income homes. Here, CO_2 reduction is higher as preferring low income homes reduces the amount of CO_2 emissions. However, it shows a slight decline compared to the optimal approach.

Figure 10 depicts the impact of skewed transition on home value. Figure 10 (left) depicts the results of skewing transition towards low income homes. The selected homes are closer to the overall median compared to the optimal approach. For example, at 5% transition, the median home value in transition is $165.2k. This represents a 11% reduction compared to the median value at optimal transition. Figure 10 (right) depicts the results of skewing transition towards high income homes. At all transition levels above 5%, the median home value in selected homes is higher than the optimal case.

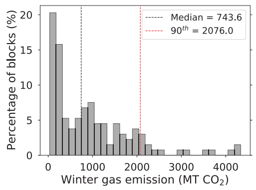


Fig. 12. *Distribution of total winter emissions by census block.*

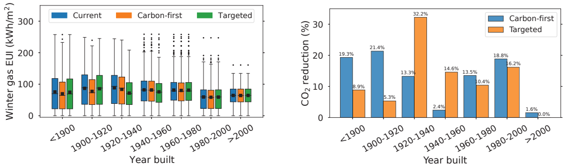


Fig. 11. *Distribution of EUI by age group at 5% transition (left), and distribution of CO_2 reduction by age group at 5% transition (right).*

5.5 Targeted transition

We next analyze the impact of targeted transition strategies on carbon emissions and EUI. As shown in §3, buildings built between the years 1920-1960 have higher energy cost per unit area than homes from the other decades. Therefore, we configure our targeted strategies to skew towards homes built during these decades. Figure 11 (left) depicts the distribution of EUI for the carbon-first and targeted strategies at 5% transition. The targeted approach prioritizes homes built between 1920-1960. The mean and median EUI after running both the carbon-first and targeted approaches are lower than the current EUI distribution. The biggest gain in EUI reduction occurs in the third bucket (1920-1940) where the average EUI in the targeted approach (19.6) is 30% lower than the average EUI in the same bucket (28). This indicates that our approach selects most homes from this bucket due to their high energy inefficiency. The targeted approach also prioritizes the targeted age groups at the expense of other age groups e.g. 1900-1920. Finally, in both approaches, at 5% transition, none of the newer homes (>2000) are selected as newer homes have higher energy efficiency than older ones.

To examine the impact of targeted transition on CO_2 reduction, we compute the CO_2 eliminated for each age bracket and compare it with the carbon-first approach. Figure 11 (right) depicts the results of this analysis at 5% transition. The emission reduction is significantly higher in the buckets between 1920-1940 compared to the carbon-first approach. This is because the targeted approach prioritizes homes in these buckets above other age groups. The figure also indicates that because of higher efficiency in newer homes i.e. post 2000, none are selected by this approach at 5% transition.

To examine the impact of targeting buildings by geographical location, we perform targeted transition by census blocks on the dataset. Figure 12 depicts the distribution of aggregate carbon emissions for census blocks in the data. The figure shows that the median block emits 743.6 MT CO_2 during winter, with most blocks emitting between 5-500 MT CO_2. The figure also shows a long tail, with some blocks emitting more than 4000 MT CO_2 (> 5× the median emission). Targeting homes by age shows that carbon reduction can be achieved by transitioning a small number of sections of the entire grid. For example, by transitioning only the top 10% highest emitting blocks, up to 33% of CO_2 emission can be eliminated.

6 RELATED WORK

Decarbonizing heating using electric heat pumps. There has been numerous studies on the viability of electric heat pumps as a replacement for gas-based heating in residential buildings [24, 25, 28, 30, 39, 40]. These studies either evaluate the performance of electric heat pumps in extreme climates or analyze their decarbonization potential at various geographical scales. Johnson et al. [23] analyze the cost of transiting to electric heat pumps and how it varies across different regions in United States. Padovani et al [29] quantify the decarbonization and economic impacts of replacing propane heating with electric heating such as solar heat pumps in rural residential buildings. While these studies focus on decarbonization benefits, they ignore equity. Our work is complementary to these studies as it introduces an equity perspective to the decarbonization process, and analyzes how such transition affects various demographics.

Impact of demographic factors on energy usage. Prior studies identify factors influencing the residential energy consumption and analyze energy profiles across socio-demographic factors such as age, income, house size, etc. Abrahamse et al. [6] show strong correlation between household energy usage and socio-demographic factors. Poortinga et al. [31] evaluate the impact of home value, income and size on energy usage. Nair et al. [27] analyzed factors influencing the adoption of investment measures to improve a building's energy efficiency e.g. income, education, age, and suggested considering such factors in promoting energy improvement investments. Our work is complementary to these studies as we quantify the impact of transition strategies that incorporate such factors.

Equity in the energy transition. Prior studies highlight social inequality in energy use and how it can inform more equitable distribution of energy resources in the energy transition. Tong et al. [38] analyzed the disparities in energy usage across different demographic profiles such as race and income. Other studies have analyzed the inequity in the energy transition and shown that lower income people and marginalized races are negatively impacted by the emerging energy transition [10, 33]. Further studies have proposed incorporating equity into the energy transition policies [15, 16]. Our work complements prior work as our optimization framework fuses together deployment of energy-efficient heat pumps for decarbonization, and incorporates equity to ensure that decarbonization is more equitable across demographic profiles.

7 CONCLUSIONS

In this paper, we conducted a data-driven analysis to quantify the decarbonization potential of an equitable transition to electric heat pumps in a city-wide distribution grid. We conducted an in-depth analysis of energy patterns of buildings, revealing a huge disparity (24%) between low and high income households. We analyzed the decarbonization potential of a strategy that prioritizes reducing carbon emissions, showing that more than 50% of CO_2 emission can be eliminated by transitioning only 40% homes. We then presented equity-aware approaches that balance the need to maximize carbon reduction with ensuring equitable outcomes for residential households. We showed that equitable strategies achieve significant carbon emissions reduction while reducing the disparity in value of the selected buildings by 5× compared to a carbon-first approach.

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