Analyzing the Impact of Decarbonizing Residential Heating on the Electric Distribution Grid

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Heating buildings using fossil fuels such as natural gas, propane and oil makes up a significant proportion of the aggregate carbon emissions every year. Because of this, there is a strong interest in decarbonizing residential heating systems using new technologies such as electric heat pumps. In this paper, we conduct a data-driven optimization study to analyze the potential of replacing gas heating with electric heat pumps to reduce CO_2 emission in a city-wide distribution grid. We conduct an in-depth analysis of gas consumption in the city and the resulting carbon emissions. We then present a flexible multi-objective optimization (MOO) framework that optimizes carbon emission reduction while also maximizing other aspects of the energy transition such as carbon-efficiency, and minimizing energy inefficiency in buildings. Our results show that replacing gas with electric heat pumps has the potential to cut carbon emissions by up to 81%. We also show that optimizing for other aspects such as carbon-efficiency and energy inefficiency introduces tradeoffs with carbon emission reduction that must be considered during transition. Finally, we present a detailed analysis of the implication of proposed transition strategies on the household energy consumption and utility bills, electric grid upgrades, and decarbonization policies. We compute the additional energy demand from electric heat pumps at the household as well as the transformer level and discuss how our results can inform decarbonization policies at city scale.

CCS Concepts: • **Mathematics of computing → Linear programming**.

Additional Key Words and Phrases: Decarbonization, Optimization, Electric Heat Pumps

1 INTRODUCTION

Residential energy usage contributes nearly 20% of all greenhouse gas emissions in the United States [13]. In 2019 alone, buildings contributed over 1850 million metric tons of greenhouse gases [1]. Heating and cooling account for roughly 38% of these emissions [24]. To avert the disastrous effects of climate change, the energy system has begun a major transition towards a carbon-free future. The building sector will play a major role in this transition.

To date, a significant fraction of buildings in colder climates, such as regions of North America and Europe, depend on natural gas, propane, or oil for residential heating in the winter. For example, 82% of Massachusetts households use non-electric sources of energy — such as utility gas, heating oil, or propane — for heating [7]. On the other hand, only 16% of households use electric heating. The low adoption of electric heating is attributed to the historical inefficiency of electric heat pumps in extremely cold climates. However, recent technological advancements have made it possible to operate electric heat pumps efficiently even at very low temperatures of -15°C [35]. This has made modern heat pumps viable candidates for replacing fossil fuel based heating even in the extreme climates of North America or Northern Europe.

Electric heat pumps offer two key decarbonization advantages over fossil fuel based heating, such as utility gas. First, they are more energy-efficient, which means they use less energy than gas furnaces to generate the same amount of heat energy [30]. Second, their reliance on electricity means that as the electric grid transitions towards greener and renewable sources for energy production, the carbon footprint of electric heat pumps will also decrease. In contrast, the carbon footprint of fossil fuel based heating will remain constant as the energy efficiency of gas furnaces is reaching its limits [12]. As a result, replacing gas furnaces with energy-efficient electric heat pumps has great potential to not only reduce a building's energy usage, but also reduce its overall carbon footprint.

A push for transition to electric heat pumps can come from either the utility or the end consumers. Although consumers do not have a direct incentive to reduce their carbon emissions, they do have a strong financial incentive to reduce their energy consumption, and ultimately their utility bills. However, the capital cost of such interventions is often a major barrier for transition. To incentivize the switch, transition strategies are typically accompanied by significant rebates and cost savings. Often, subsidies provide assistance to make a building more energy efficient as a whole. For instance, in some states in the U.S., heat pump rebates can be as high as $10, 000, and are accompanied with an additional 75-100% rebate for adding new insulation to the building envelope [28]. Despite these subsidies, consumers are still expected to make a major upfront investment, which presents a financial hurdle for many customers. Utilities, on their own, also do not have any financial incentives for decarbonization, which can require upgrades in the electric grid, as well as retiring parts of the gas network infrastructure before its natural end of life. However, they are increasingly being required by government policy or regulations to reduce carbon emissions in line with commitments made at the UN's Paris Climate Agreement to limit the global temperature rise to less than 2°C [3].

Any transition strategy, be it from a utility's perspective or a consumer's, requires identifying a set of buildings to be retrofitted with heat pumps. The selection of buildings is non-trivial and traditionally depends on various factors, such as the total energy consumption and insulation levels. However, for decarbonization, two of the most important factors are the total carbon footprint and the carbon-efficiency of a building. The total carbon footprint quantifies the total amount of emissions from heating, irrespective of how much heat was generated and the efficiency of the process. Carbon efficiency, on the other hand, quantifies the amount of heat generated per unit of carbon emitted. The two metrics are related but distinct. For example, a building may have a large total carbon footprint, but be highly carbon-efficient. Therefore, while a carbon reduction strategy that targets the highest emitting buildings yields the greatest *initial* reduction in CO_2 emissions, it does not fully exploit additional opportunities for improvements, such as increasing building energy efficiency. In addition, there are additional questions that need to be answered. How does the choice of one metric

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impact the other? How does carbon-efficiency differ from energy-efficiency from a decarbonization standpoint? How does carbon emission reduction impact energy consumption (also a proxy for heating cost) for the end consumers? Finally, since the transition is not instantaneous but rather a gradual process, which buildings should be transitioned first, and which should come later? The answers to these questions are non-trivial and require an in-depth analysis of real energy consumption data.

Furthermore, a transition from gas-based heating to electric heat pumps has an impact on the energy consumption and the utility bills for the household. From a consumer's perspective, an energy transition strategy should not increase the energy consumption and the electricity bills. Similarly, such a transition will add additional electric load to the grid and may trigger upgrades of electric grid components at home, such as service meters, and other distribution grid infrastructure, such as service lines and transformers. From a utility's perspective, an energy transition strategy should not trigger updates of electric grid components and should delay them to as far into the future as possible. Finally, from the perspective of policy makers, a transition analysis should provide concrete guidelines that inform the design of city-scale decarbonization policies.

In this paper, we conduct a data-driven optimization study to analyze the potential carbon emission reductions from replacing gas-based heating with electric heat pumps in a city-wide distribution grid. Our empirical study is based on analyzing real natural gas and electric data from 13,800 and 6,445 smart electric and gas meters respectively collected over a one year period. We conduct an in-depth analysis of the heating demand of buildings and quantify their carbon footprint. We quantify CO_2 emission reductions obtained when a carbon-optimal transition strategy is applied to the conversion from gas to electric heating. We then introduce additional goals such as CO_2 efficiency and improving building efficiency to take advantage of further energy improvements in addition to CO_2 reduction. In conducting our empirical analysis, this paper makes the following contributions.

Energy Consumption and Emission Analysis. We use a city-scale dataset to conduct an in-depth analysis of its gas consumption and the resulting CO_2 emissions. One of our key findings is that the median building produces ≈ 32 MT of CO_2 annually, with some buildings emitting $\geq$250MT CO_2, which is 7.8× the median. This analysis motivates transition strategies that target buildings with higher emissions to meet aggressive decarbonization goals.

Optimal CO_2 Reduction. We present a multi-objective optimization (MOO) framework that enables the flexible selection of a subset of homes for heat pump retrofits to achieve decarbonization goals. Our analysis of a transition and building selection strategy that achieves maximum possible initial CO_2 reductions suggests that it fails to take advantage of other aspects of energy transition such as improving energy and carbon efficiency in buildings. Consequently, we update our multi-objective optimization framework to consider additional objectives of energy efficiency and carbon efficiency.

Joint CO_2 and energy-efficiency optimization. In addition to a carbon emissions analysis, we analyze the energy inefficiency of buildings and its causes. We show energy efficiency can be improved by transitioning buildings from gas to electric heat pumps, to reduce emissions, while simultaneously improving energy efficiency via renovations, such as adding insulation to the building. We show the effect of prioritizing energy efficiency on energy demand and CO_2 emissions. Our analysis finds that older buildings are generally less efficient and should be prioritized in transition.

Implications of transition strategies and takeaways. Finally, we provide a detailed analysis of the impact of proposed transition strategies on household energy consumption and utility bills, additional load on the electric grid at various spatiotemporal scales, and the design of city-scale decarbonization policies.

2 BACKGROUND

In this section, we present background on the energy transition, decarbonization of heating, and electric heat pumps.

2.1 Energy Transition

The U.S., along with most countries in the world, still relies on non-renewable, fossil fuel-based energy sources — such as coal, natural gas — for a majority of its energy needs. For example, fossil fuel-based energy resources fulfilled more than 79% of U.S. energy consumption in 2021 [1]. To curtail the effects of climate change, there is a push towards cleaner sources of energy. The energy transition can be achieved individually for each of the major sectors of energy consumption, such as transportation, buildings, and agriculture. However, prior studies have suggested that a more effective pathway is to transition our energy needs to electricity while intensifying efforts to clean the sources of electricity production [22]. This hypothesis is supported by recent estimates that suggest that the carbon intensity of electricity (in g·CO_2/kWh) in the U.S. decreased 30% between 2001 and 2017, largely due to the replacement of coal-fired power plants with natural gas and wind generation [34]. This trend is expected to continue as the use of renewable energy resources for electricity production increases. The electrification of buildings and transportation has received significant attention to accelerate the energy transitioning progress. In this paper, we quantify the impact of electrifying heating in the building sector via electric heat pumps on energy consumption and CO_2 emissions, an important step for energy transition.

2.2 Decarbonizing Heating

Heating using fossil fuels, such as natural gas, propane and oil, accounts for more than 47% of overall heating energy consumption in United States [11]. Natural gas and propane furnaces use a gas burner to heat air or water, which is then circulated to heat the building. The combustion of natural gas produces carbon dioxide as a byproduct, which is released into the atmosphere. Heating and cooling in the residential sector is responsible for more than 38% of all CO_2 emissions in United States every year [24]. The decarbonization of heating is an important step towards achieving overall carbon reduction goals. The decarbonization of heating, to various degrees, can be achieved in multiple ways by transitioning to geothermal heating, hybrid heating, and/or electric heat pumps. Heating through geothermal energy is an emerging technology, but may not be suitable for all locations [37]. Hybrid heat pumps combine electric heating with a secondary fuel, such as a propane tank. While these options may be cost-effective solutions in the short term, they are not a long-term solution if society is to transition to a carbon-free future. The use of energy-efficient electric heat pumps has been proposed as an ideal pathway to decarbonization of the future grid [5, 6, 17, 20, 38]. As the electric grid transitions towards a carbon-free future, discussed in Section 2.1, the heating sector will need to organically transition to a carbon-free future.

2.3 Electric Heat Pumps

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. Conversely, during summer seasons, a heat pump moves heat from within a building to the outside atmosphere which cools the inside of the building. 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.

The most popular type of heat pump available in the market today is an air-source heat pump [30], which transfers heat between the inside of a building and the outside air. Because these heat pumps rely on air heat transfer, as the outside temperature decreases, their heating efficiency reduces. In the past, such heat pumps required a backup energy source to be used during extremely low temperatures, such as a gas furnace or electric heating [15]. However, recent advances in heat pump technology have made them efficient even at low temperatures, which makes them an ideal replacement for gas heating even in cold climates [10, 35]. 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 lower than that of natural gas. Moreover, due to their reduced energy usage, heat pumps can reduce the cost of heating a building by up to 60%. This makes them an attractive source of heating from a carbon, energy efficiency, and cost perspective.

2.4 Electric Distribution Grid

In analyzing the impact of transition to air-source electric heat pumps on the electric grid, this work focuses on the distribution segment of the electric grid which supplies electricity to the residential households. While the distribution grid consists of many components including electric substations, feeders, distribution lines, and transformers, we only focus on the distribution grid infrastructure at the household and transformer level. This is because our dataset does not include the electric grid information except the service meters connected to the individual households and the distribution transformer on per-block basis. As a result, our electric grid impact analysis only looks at the additional load at the level of households and the distribution transformers at the edge.

The distribution transformers at the edge vary in their capacity, ranging from 5-50 kilo-Volt-Ampere (kVA) mounted on pole-tops, to large 75-225 kVA transformers mounted on pads. The size of the transformer at a given location depends on the expected peak load of the buildings served by the transformer. The transformers generate heat due to energy losses during their operation and have safety mechanisms such as mineral oil that absorb the generated heat. Due to these safety mechanisms, transformers can operate above their rated capacity (upto 125%) but a prolonged operation under such condition can generate excess heat to evaporate the oil and melt the transformer coils. The operation beyond the rated capacity reduces the efficiency of the transformer, decrease its lifetime, and cause power outages.

Table 1. Summary of Key Data Characteristics

No. of electric meters	13,800
No. of gas meters	6,445
Granularity of gas data	1 hour
Granularity of electric data	5 minutes
Duration	Jan 2020 - Dec 2020

3 PROBLEM AND METHODOLOGY

In this section, we present the problem statement and key research questions we address in the paper. We also describe the datasets and experimental methodology we use to answer these questions.

3.1 Problem Statement

Given a set of residential buildings in a city or town, the primary goal of our work is to quantify the impact of replacing gas heating with electric heat pumps on carbon emission reductions, and the optimal order in which homes should be transitioned. Another goal is to understand the impact of introducing additional goals such as carbon-efficiency and energy inefficiency in buildings as priorities for such a transition, and the tradeoffs such goals have on emissions reduction. Specifically, we seek to answer the following questions.

(1) What is the distribution of heating energy consumption, and how much gas is required to meet these heating requirements? What are the daily and seasonal variations in gas consumption? How much CO_2 is emitted from this gas consumption, both for individual residential buildings and in the aggregate?
(2) What is the impact of replacing gas heating with electric heat pumps on energy consumption and CO_2 emissions? What is the optimal order in which buildings should be transitioned from gas to electric heat pumps in order to minimize CO_2 emission?
(3) How is this ordering impacted when additional goals such as carbon/energy inefficiency of buildings are introduced? How is CO_2 reduction impacted, and what are the tradeoffs?

3.2 Description of Datasets

The answers to these questions vary based on region and largely depend on seasonal factors such as the severity of winter weather, which in turn influences gas demand for heating. Other factors such as type and purpose of building e.g. industries, factories may also affect energy patterns. In this paper, we focus on residential data collected from a small city in the Northern region of United States. Since the gas and electric system design in this city is typical of many regions across the world, and residential usage is invariant across regions, we believe that our insights are widely applicable.

Gas and Electric Usage Data. Our dataset consists of electric and gas consumption data recorded by 13,800 electric and 6,445 gas meters. The data also includes a mapping of electric and gas meters installed at each building. To compute the aggregate load profile of a building, we sum up the load from the electric and gas meters installed in the building. Electricity demand data is recorded at 5 minute granularity and spans >5 years. Gas consumption data is recorded at hourly granularity, and spans the same duration. For the

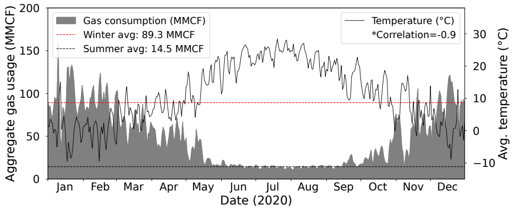


Fig. 1. *Aggregate gas demand during the year 2020.*

purpose of our study, we limit our analysis to the full calendar year 2020, which is the latest year whose complete data was available. Note that some households rely on other sources of fuel for heating (e.g. oil, propane, electricity), and therefore only have one electric meter, and the number of electric meters is higher than that of gas. Table 1 shows a summary of the characteristics for this dataset.

Building Property Data. In addition to load data, we collect property data for all buildings present in our dataset using public real-estate records. This includes the size of the building, type of building, e.g., single vs multi-family, etc. We use this data to augment out analysis, e.g., to generate a building's energy profile, we normalize the load by the building's size to enable comparative analysis across different buildings. We gather and parse this data from publicly available property information recorded as part of tax records.

Weather Data. Since our analysis involves measuring the impact of weather on energy usage, we gather weather data for the city from the Dark Sky API [1]. We collect multiple data points such as temperature, humidity from the API. We gather this data at hourly granularity to match our hourly gas load data.

4 ENERGY USAGE AND CARBON ANALYSIS

To understand the impact of transitioning buildings from gas to electric heat pump heating, we begin with an analysis of the current load on the gas system and the resulting CO_2 emission. Specifically, we study the daily, seasonal and annual variations in gas energy usage across the whole system.

4.1 Energy Demand Analysis

Figure 1 depicts the aggregate gas demand for the city under-consideration over the course of an year. There are two peak periods — between Jan-Feb and Nov-Dec months. These peaks coincide with the most severe winter months. The average daily gas demand during winter months is 89.3 MMCF (million cubic feet), which is 6× the daily average during summer months (14.5 MMCF). The data also demonstrates a strong negative correlation (-0.9) between temperature and gas demand — as the temperature falls, gas demand rises due to increased residential heating in buildings. Figure 2(a) depicts the daily aggregate demand for gas across the system. The figure shows that on most days, aggregate demand is < 25 MMCF. This is mainly due to the use of non-heating appliance such as stoves. The figure also shows a spread of high usage days during which demand is highest. For instance, the peak day consumes > 150 MMCF, which is 3.5× the average usage. Since these high usage days are predominantly made up of heating consumption, replacing gas heating with electric heat pumps has great potential to curtail CO_2 emission.

[1] https://darksky.net/dev

In addition to analyzing the aggregate daily demand, we study the variation in gas demand by time of day, and the periods during which the daily peak demand occurs. Figure 2(b) depicts the average gas demand by time of day during winter and summer months. During winter, gas demand exhibits a bi-modal peak — a sharp peak between 8-9am, and a moderate peak between 5-8pm. This coincides with the morning and evening routines during which occupancy and activity in homes is highest. The peak hourly demand is 5.08 MMCF, while the average demand is 3.72, indicating a 1.4 peak-to-average ratio. Lastly, gas demand during summer months does not show significant variation over the course of the day. This is because gas usage during summer is predominantly made up of appliance usage which is fairly constant throughout the year.

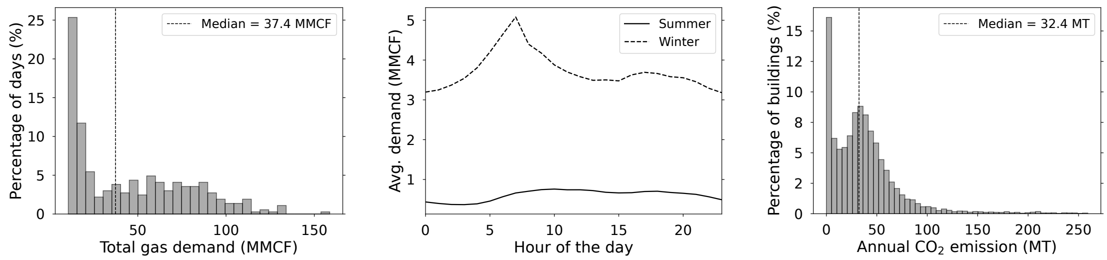
4.2 Carbon Emission Analysis

The combustion of natural gas produces carbon dioxide as a byproduct which is released into the atmosphere. When gas is used for heating, the amount of CO_2 emitted is driven by the amount of gas required to generate enough heat for a building. This is in turn driven by the temperature e.g. as the temperature decreases, more heat is required to raise the indoor temperature, as well as the building size i.e. larger spaces require more energy to heat. Further, building characteristics such as insulation affect how much gas is consumed e.g. buildings with poor insulation lose heat to the atmosphere faster than those with better building envelope, and therefore have higher gas demand.

To examine the CO_2 emission generated directly from gas heating, we compute the emission for each building by multiplying the total gas consumption for the year with the emission factor of gas. About 0.0551 MT of CO_2 is produced for each MCF of natural gas burned [2]. To estimate heating gas consumption, we subtract summer average from the overall gas usage. This accounts for other uses of natural gas that may be present in a household e.g. stoves, water heating, etc. Figure 2(c) depicts the distribution of CO_2 emitted by each building from heating gas combustion. The figure shows that the median building emits 32.4 MT of CO_2 every year. The figure also shows a long tail, with a small number of buildings emitting a lot more CO_2 compared to others. These buildings are particularly good candidates for transition to a more sustainable heating source in order to reduce their CO2 emissions. The highest emitting buildings contribute >250 MT CO_2 during the year which is 8.1× the median emission and 7× the average CO_2 emission.

5 MULTI-OBJECTIVE DECARBONIZATION

In this section, we present a data-driven multi-objective optimization (MOO) framework that enables flexible selection of a subset of homes for heat pump retrofits to achieve decarbonization goals. We start the optimization with an initial goal of maximizing CO_2 reductions and iteratively add additional objectives of maximizing carbon efficiency and targeting energy inefficient buildings. In doing so, our formulation enhances decarbonization to not only aim for the highest emitters, but also target smaller buildings that have a smaller CO_2 footprint but are CO_2 or energy inefficient, with the aim of achieving a balanced transition. While the optimization can be extended to other objectives, in this work, we focus on CO_2 reduction, CO_2 efficiency and energy efficiency.



(a) Aggregate Daily Gas Demand (b) Avg. Gas Demand by Hour (c) CO_2 Emissions

Fig. 2. *Probability distributions for aggregate daily gas demand (a), average gas demand over the course of the day (b), and CO_2 emissions from buildings throughout the year.*

5.1 Optimizing for Carbon Emissions Reduction

Let $H = \{h_1, h_2 ... h_n\}$ denote the set of buildings, each indexed by i. Let C_i^g denote the total CO_2 emission from the cumulative gas consumption for building i required for heating during the year. Let C_i^e denote the total CO_2 emission from the cumulative electric consumption for building i required for heating when using an electric heat pump. Let α_i represent the transition-to-electricity status for the building i and S represent the denote the target number of buildings to transition to electric heat pump heating.

Given that, our objective is to select S buildings from the set H which when transitioned to electric heat pumps result in the lowest aggregate CO_2 emission possible across buildings. This objective can formally be described as follows.

$$\begin{aligned} \min \quad & \sum_{i=1}^{n} (1 - \alpha_i) \cdot C_i^g + \alpha_i \cdot C_i^e \\ \text{s.t.,} \quad & \text{Equations (2) - (4)} \\ \text{vars.,} \quad & C_i^g, C_i^e, \alpha_i, S \quad \forall i \end{aligned} \tag{1}$$

Our first constraint relates to to the level of transition. Let α_i denote a binary variable which indicates the state of transition for each building i such that $\alpha_i \in \{0, 1\}$. When set, the building is transitioned to electric heat pump heating, and when not set, the building remains on gas. Further, let S denote the target number of buildings to transition to electric heat pump heating. To ensure that only S buildings are transitioned, the sum of all values of α_i must equal S, as stated below.

$$\sum_{i=1}^{n} \alpha_i = S \tag{2}$$

Our final set of constraints simply ensure that a building cannot have negative carbon emissions from either the gas consumption or the electric demand.

$$C_i^g \geq 0 \quad \forall i \tag{3}$$

$$C_i^e \geq 0 \quad \forall i \tag{4}$$

The total CO_2 emission from gas consumption, C_i^g, over the course of an year for a building i is a multiple of the total heating gas demand D_i^g and the carbon intensity of gas I_g.

$$C_i^g = D_i^g \times I_g \tag{5}$$

The total CO_2 emission from electric demand, C_i^e, over the course of an year for a building i is a multiple of the total electricity demand D_i^e and the carbon intensity of the electric grid I_e.

$$C_i^e = D_i^e \times I_e \tag{6}$$

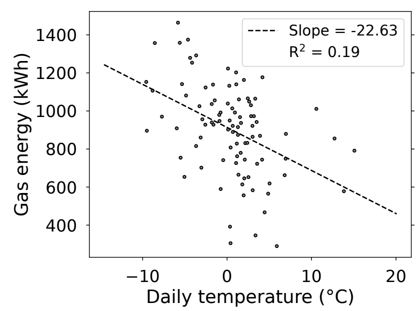


Fig. 3. *Relationship between the energy generated from gas consumption and temperature.*

It should be noted that a simple ordering of homes based on their total carbon emissions can achieve the singular goal of selecting a set of buildings that maximizes carbon emission reductions after transition. However, we present this as a flexible multi-objective optimization framework so that additional objectives, discussed in subsequent sections, can be integrated into the same framework.

5.2 Optimizing for Carbon-efficiency

Optimizing for total carbon emission reduction targets buildings with highest carbon footprint. However, the large footprint may be a result of large residential area or large number of residents and the building itself may be making a highly efficient use of its gas demand. With CO_2 reduction as the sole goal, only larger buildings will be selected, and many smaller highly inefficient buildings will be left out. To capture this effect, we define the notion of *carbon-efficiency*. We define *carbon-efficiency* as the amount of CO_2 emitted when one unit area of a building is raised by one unit of temperature. We further elaborate the notion of *carbon-efficiency* next.

The notion of *carbon-efficiency* is based on the observation that electric heat pumps consume lower energy compared to gas to heat the same building from a lower temperature T_{low} to a higher temperature T_{high}. Figure 3 depicts the relationship between energy generated from gas consumption and temperature for a building during winter months. The figure shows an inverse relationship between energy and temperature. As the temperature decreases, the energy required to heat the building increases. The rate of change (captured in the slope of the fit line) indicates the amount of energy required to raise the building's temperature by one unit of temperature. This is directly proportional to the CO_2 produced for each unit temperature. To measure how well the fit line fits the energy and temperature data, we compute coefficient of determination, R^2

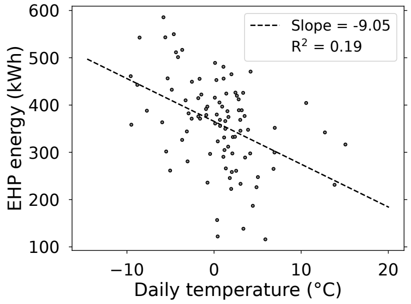


Fig. 4. *Relationship between energy demand of an electric heat pump and the temperature.*

(0.19). Since we consider a coarse granularity of energy and temperature data i.e. average across a whole day, the R^2 value is adequate. We do this for both energy and gas usage data.

Figure 4 depicts the relationship between the energy demand of an electric heat pump and the temperature for the same building. Similar to gas energy consumption, there is an inverse relationship between electric energy and temperature. However, the slope is significantly less steep than that of gas. This is because electric heat pumps consume lower electrical energy to generate the same amount of heat energy. Since carbon emissions are directly proportional to energy consumption, the CO_2 produced for each unit temperature is lower for electric heat pumps. Since buildings have different sizes, energy consumption alone is not enough to compare usage between buildings of varying size. Before computing the energy slope, we normalize both gas and electric heat pump energy by size. We then compute carbon emissions per unit size.

Note that maximizing carbon efficiency introduces a tradeoff between reduction and efficiency. Since the most carbon efficient buildings are not necessarily the highest emitters in absolute scale, a portion of CO_2 reduction must be foregone to maximize efficiency. However, since gas furnaces are inherently inefficient, maximizing carbon efficiency places a tighter bound on wasted CO_2 emission, and leads to better energy utilization. We extend the multi-objective optimization framework defined in Equation 1 to jointly maximize the *carbon-efficiency* and minimize the total carbon emissions. In doing so, we introduce a new set of variables that are defined next.

First of all, we use the absolute value of the carbon emission slopes for both gas and electricity as a substitute for *carbon-efficiency*. This formulation of the problem allows us to keep the overall objective as minimization of carbon emission reductions and slopes of the emission curves (representing carbon-efficiency). Given that, let λ_i^g be the absolute slope of gas CO_2 emissions for the building i. Let λ_i^e be the absolute slope of electric CO_2 emission for the building i. Our joint optimization of minimizing carbon emissions and maximizing carbon-efficiency can be stated as follows.

$$\begin{aligned} \min \quad & \sum_{i=1}^{n}(1-\alpha_i)\cdot C_i^g + \alpha_i \cdot C_i^e \\ \min \quad & \left[\sum_{i=1}^{n}(1-\alpha_i)\cdot \lambda_i^g + \alpha_i \cdot \lambda_i^e\right]\cdot \frac{1}{n} \\ \text{s.t.,} \quad & \text{Equations (2) - (4)} \\ \text{vars.,} \quad & C_i^g, C_i^e, \alpha_i, \lambda_i^g, \lambda_i^e, S \quad \forall i \end{aligned} \tag{7}$$

As stated before, to maximize CO_2 efficiency, we minimize the average absolute slope of CO_2 emissions curve across all buildings.

5.3 Targeting Energy Inefficient Buildings

In addition to *carbon-efficiency*, building decarbonization strategies may also want to target energy inefficient buildings. Energy efficiency in transition is important for two main reasons. First, higher efficiency translates to a lower carbon footprint. Second, since nearly half of a building's energy usage results from heating and cooling alone, improving efficiency of heating is one of the most effective ways for reducing a building's energy bill.

The sources of energy inefficiencies include poor insulation, high temperature set points for heating and cooling, and inefficient appliances. In this section, we extend our optimization formulation to target buildings that have one or more energy inefficiencies. To do so, we extend our analysis to not only consider gas energy usage only, but also electric usage. We learn a building energy model and use it to identify energy inefficiencies which we target in decarbonization.

Let $U = \{h_1, h_2 ... h_p\}$ denote the set of buildings with heating inefficiency i.e. high heating slope, each indexed by k. Let $V = \{h_1, h_2 ... h_q\}$ denote the set of buildings with cooling inefficiency i.e. high cooling slope, each indexed by l. Further, let $W = \{h_1, h_2 ... h_r\}$ denote the set of all other buildings i.e. all buildings with any other inefficiency except heating and cooling, as well as those without any inefficiency, each indexed by m.

Let $C_k^{g,u}$, $C_l^{g,v}$ and $C_m^{g,w}$ be the total carbon emissions from gas consumption in heating inefficient, cooling inefficient, and the remaining buildings, respectively. Further, let $C_k^{e,u}$, $C_l^{e,v}$ and $C_m^{e,w}$ be the total carbon emissions from electricity usage in heating inefficient, cooling inefficient and remaining buildings, respectively. Let ζ_k, β_l and γ_m be the binary variables that indicate the transition status of heating inefficient, cooling inefficient, the remaining buildings, respectively. All of the binary variables can only take a value of either 0 or 1, which means that $\zeta_k, \beta_l, \gamma_m \in \{0, 1\}$ for all k, l, and m. To transition only S buildings, the sum of all set variables from all building groups must be equal to S.

$$\sum_{k=1}^{p}\zeta_k + \sum_{l=1}^{q}\beta_l + \sum_{m=1}^{r}\gamma_m = S \tag{8}$$

Lastly, since buildings cannot have negative energy usage and therefore negative emission, we ensure that emission from buildings in all groups is greater than or equal to zero.

$$C_k^{g,u}, C_l^{g,u}, C_m^{g,v}, C_k^{e,v}, C_l^{e,v}, C_m^{e,w} \geq 0 \quad \forall k, l, m \tag{9}$$

With these constraints in place, our objective is to select S buildings from the sets U, V and W such that when the S buildings are transitioned to electric heat pumps, carbon emissions are minimized, while the portion of S buildings selected from the heating and cooling inefficient groups is maximized. This multi-objective optimization problem can be formally stated as follows.

$$\begin{aligned} \min \quad & f_u(u) + f_v(v) + f_w(w) \\ \min \quad & \sum_{k=1}^{p}(-1\cdot\zeta_k) + \sum_{l=1}^{q}(-1\cdot\beta_l) \\ \text{s.t.,} \quad & \text{Equations (8) - (9)} \\ \text{vars.,} \quad & C_k^{g,u}, C_l^{g,v}, C_m^{g,w}, C_k^{e,u}, C_l^{e,v}, C_m^{e,w}, \zeta_k, \beta_l, \gamma_m, S \quad \forall k, l, m \end{aligned} \tag{10}$$

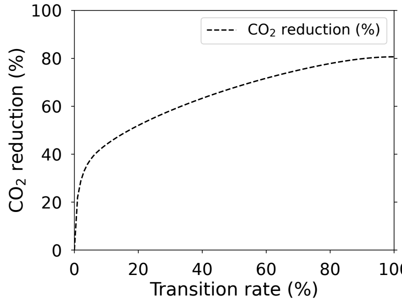


Fig. 5. *Reduction in carbon emission at varying levels of transition from gas-based heating to electric heat pumps.*

The composite functions f_u, f_v, and f_w are defined as follows.

$$f_v(u) = \sum_{k=1}^{p}(1-\zeta_k)\cdot C_k^{g,u} + \zeta_k \cdot C_k^{e,u} \tag{11}$$

$$f_u(v) = \sum_{l=1}^{q}(1-\beta_l)\cdot C_l^{g,v} + \beta_l \cdot C_l^{e,v} \tag{12}$$

$$f_w(w) = \sum_{m=1}^{r}(1-\gamma_m)\cdot C_m^{g,w} + \gamma_m \cdot C_m^{e,w} \tag{13}$$

Note that to maximize the number of buildings selected from the heating and cooling inefficient groups, we minimize the negation of all set binary variables from the two sets.

6 EVALUATION

In this section, we present the results for various decarbonization strategies presented in Section 5 and evaluate their efficacy in reducing carbon emissions and increasing energy efficiency. To do so, we introduce varying levels of transition across the system — where the transition rate represents the percentage of buildings converted from gas to electric heat pumps.

6.1 Experimental Setup

The gas and electricity consumption data from the buildings (described in Section 3.2) provides building-level metering of the gas and electricity demand. We first disaggregate gas and electric demand data into two components: first, used for heating purposes, and second, used by all the other appliances such as stoves. To do so, we compute the average gas usage during the summer, and subtract it from the year-round data to get the heating component of gas usage. This removes usage from other appliances such as stoves, and ensures we estimate CO_2 reduction from heating only. We also account for energy loss due to the inherent inefficiency of gas furnaces. To do so, we use an efficiency level of 87.5%, which lies between the typical efficiency of a standard and a high efficiency furnace. To compute total carbon emissions from gas usage, we use a gas carbon intensity value of 0.0551 MT/MCF [2].

To compute the corresponding electric heat pump emissions, we compute the total heat energy generated by the volume of gas consumed and use the Heating Seasonal Performance Factor (HSPF) of electric heat pumps to compute the electric energy required to generate the equivalent amount of heat energy. For all experiments, we assume a HSPF rating of 8.5, which is typical of many efficient heat pump models. Finally, to compute the carbon emissions from electric heat pump usage, we use a carbon intensity value of 0.000386 MT CO_2/kWh, corresponding to the average carbon intensity value for the United States electric grid [34].

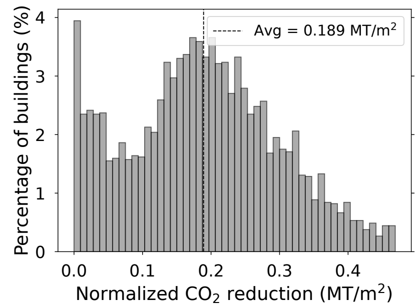


Fig. 6. *Distribution of normalized carbon emissions reduction across all buildings in our dataset.*

Finally, to perform evaluation, our experimental setup makes a few assumptions. First, we use a coarse grained emission factor of electricity, as well as efficiency levels of gas furnaces. Second, to learn building energy models, we assume that high granularity energy and temperature data are available. While availability of the former varies from region to region and depends on the pervasiveness of smart meters, the latter is widely available.

6.2 Optimizing Carbon Emissions Reduction

We first analyze the impact on carbon emissions after transitioning buildings from gas to electric heat pumps using a strategy that optimizes carbon emission reductions. At each transition level, the buildings that lead to the highest reduction in carbon emission are selected for transition. We run this optimization on our gas consumption data and compute the resulting carbon emission at each transition level. Figure 5 presents the results for this analysis and there are two interesting observations. First, carbon emissions reduce at an exponential rate at the lower levels of transition i.e. 1-10%. This is because since we are only optimizing for carbon emissions reduction, the biggest emitters are selected first, which leads to a disproportionately high carbon emissions reduction at the start. As transition rate increases, carbon emission reductions enter another phase characterized by a linear growth (with low slope) from 10-100%, where the rest of buildings with moderate emissions are transitioned. Second, results also shows that at 100% transition, electric heat pumps have the potential to cut carbon emissions by up to 81%. This is a noteworthy observation, and demonstrates the viability of heat pumps to replace natural gas for heating and at the same time, helping make significant strides towards decarbonizing the building sector and achieving climate goals.

We next analyze the carbon emission reductions per unit area. We compute the total carbon emission reductions for each building, and normalize the difference with the size of the building. Figure 6 depicts the distribution of carbon emission reductions per unit area across all buildings. The figure shows that normalized CO_2 reduction is normally distributed with the average building seeing an annual reduction of 0.189 MT/m^2. Given that the median house size of single family home in United States is 2273ft^2 (211.17m^2) [8], each home has a potential to reduce 40.9 MT each year.

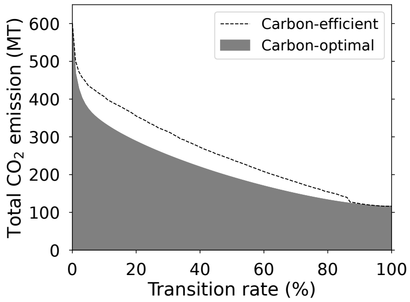


Fig. 7. *Carbon emissions at varying levels of transition from gas-based heating to electric heat pump while jointly optimizing for carbon emissions reduction and carbon-efficiency.*

Table 2. Probable building faults alongside their underlying characteristics.

Indicator Characteristics	Probable Faults	Optimization Group
High heating slope	Inefficient heater, Poor building envelope	Inefficient heating
High cooling slope	Inefficient HVAC, Poor building envelope	Inefficient cooling
High heating temperature	High set point, Poor building envelope	Other
Low cooling temperature	Low set point, Poor building envelope	Other
High base load	Inefficient appliances	Other

6.3 Maximizing Carbon-efficiency

Next, we analyze the impact of optimizing for carbon-efficiency on carbon emissions reduction. The goal here is to quantify the tradeoff between carbon emissions reduction and efficiency, i.e. how much carbon emissions can be eliminated while also ensuring that carbon emissions per unit area is minimized. We solve the optimization problem described in Section 5.2 and compare the aggregate carbon emissions after the transition with the carbon-optimal strategy results presented in Section 6.2. Figure 7 depicts the results for this analysis. The figure shows that carbon emissions reduction is lower than the optimal case for up to $\approx 85\%$ transition, after which carbon emissions are similar to the optimal scenario. The magnitude of initial growth of CO_2 reduction is also lower. This is because some of the highest emitting buildings have high carbon efficiency. This indicates a tradeoff between absolute reduction and efficiency i.e. in joint optimization, some large emitters are foregone in favor of less-efficient buildings which have a lower absolute carbon footprint. The largest deviation occurs at 15% transition, where 71 GT of carbon emissions reduction is foregone in favor of maximizing efficiency. However, carbon-efficiency increases by 1.9×. Utility companies can therefore choose between efficiency and absolute reduction in carbon emissions depending on the weight associated with each outcome. Since there is not a significant deviation in carbon emissions reduction, utility companies can maximize carbon-efficiency while sacrificing only a small amount of carbon emissions reduction compared to the optimal case.

6.4 Targeting Energy Inefficient Buildings

We next examine the tradeoff in carbon emissions reduction introduced by prioritizing inefficiencies in buildings. We begin by performing building segmentation based on their unique energy inefficiencies and the underlying faults that cause such inefficiencies. Our fault analysis is based on the technique proposed in [18].

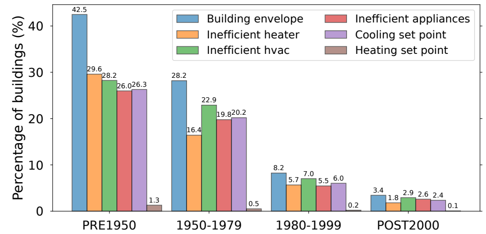


Fig. 8. *Distribution of energy inefficiencies across buildings by age group.*

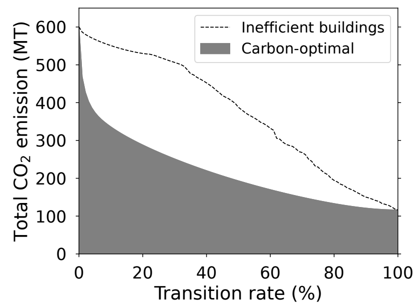
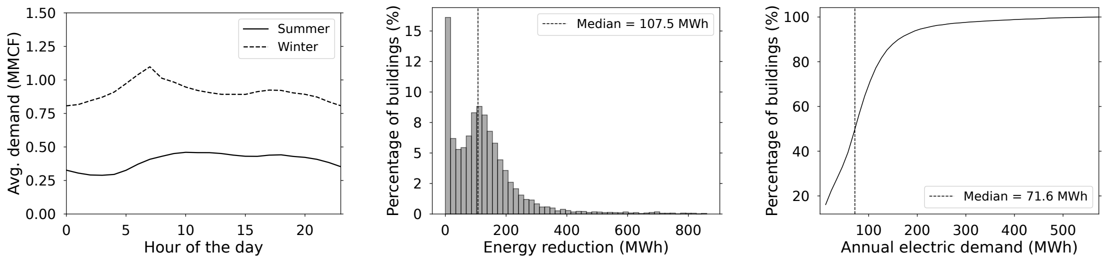


Fig. 9. *Carbon emissions at varying levels of transition to electric heat pumps from gas-based heating while jointly optimizing for carbon emissions reduction and targeting energy inefficient buildings.*

We apply the proposed technique to our data. Table 2 shows the indicator characteristics identified for each building along with the possible faults that underlay such inefficiencies. The third column shows the optimization group that we place each building in based on the identified characteristics. Specifically, we target homes that have heating and cooling inefficiencies since these would benefit most from transitioning from gas to electric heat pumps.

Figure 8 depicts the distribution of energy inefficiencies identified in buildings in our dataset. The figure shows that poor building envelope is the leading cause of energy inefficiency. This is true across buildings of all age groups. It also reveals that inefficient HVAC and heating units are the second and third most prevalent causes of energy inefficiencies of buildings, respectively. Since electric heat pumps are capable of operating as both heating and cooling units based on the season, this distribution of faults underpins the importance of targeting energy inefficient buildings in transition. The figure also shows that older buildings are more prone to being energy inefficient, while newer buildings show less prevalence probably due to improved building standards. This segmentation of buildings based on underlying energy inefficiency informed the basis of our targeted optimization, presented in Section 5.3. Targeting inefficient buildings offers multiple advantages over optimizing for carbon emissions alone. For example, transitioning to electric heat pumps typically comes with additional benefits such as building retrofits. This enables buildings to take advantage of these additional benefits during transition. Moreover, the amortized cost of transition may be reduced by performing multiple upgrades at once.

To quantify the tradeoff in carbon emissions reduction and targeting inefficiency buildings, we run the optimization described in Section 5.3 on our datasets and compare the resulting carbon emissions reduction with the carbon optimal scenario. Figure 9 depicts the results of this experiment, and presents some interesting observations. First, carbon emissions reduction show a gradual linear



(a) Hourly gas demand (b) Energy consumption reduction (c) Additional electricity demand

Fig. 10. *Distribution of (a) average gas load demand by time of day after transitioning to electric heat pumps, (b) energy consumption reduction across buildings after transition to electric heat pumps, and (c) additional electric demand exerted on the system after transitioning from gas to electric heat pumps.*

decrease from start to finish compared to the optimal case, and only converges at near full transition (≈ 98%). Since older buildings are more prone to energy inefficiency, this figure also indicates that this strategy has the effect of selecting older buildings first. Similar to optimizing for carbon efficiency, targeting inefficient buildings introduces a tradeoff between absolute reduction and improving energy efficiency. We find that the highest emitters are not necessarily the most energy inefficient. Since the end goal in both cases is CO_2 reduction, utility companies can choose to forego one for the other depending on the weight associated with each outcome.

Finally, we evaluate the impact of transitioning to electric heat pumps on the daily gas demand. Figure 10(a) depicts the average hourly demand of gas during winter and summer months after 100% transition to electric heat pumps. Similar to the observations made in Figure 2(b), we find that gas demand exhibits a bi-modal peak — between 8-9am and 5-8pm. The figure also makes two interesting observations. First, the average peak demand reduces by 78% compared to the case before transition. Second, the extremity of the peak is also reduced significantly. Before transition, the peak demand was 1.4× the average hourly demand. Post transition, the peak-to-average ratio is 1.2, indicating a 14.3% reduction compared to the value before transition. Lastly, the figure shows no significant change in daily usage pattern of gas during summer months since consumption is mainly made up of appliance usage which does not change with the introduction of heat pumps.

7 IMPLICATIONS AND TAKEAWAYS

In this section, we discuss the implications of our approach on the household energy consumption, transformer upgrades in the electric grid, and broader decarbonization policy objectives at city-scale.

7.1 Impact on Energy Consumption Reduction

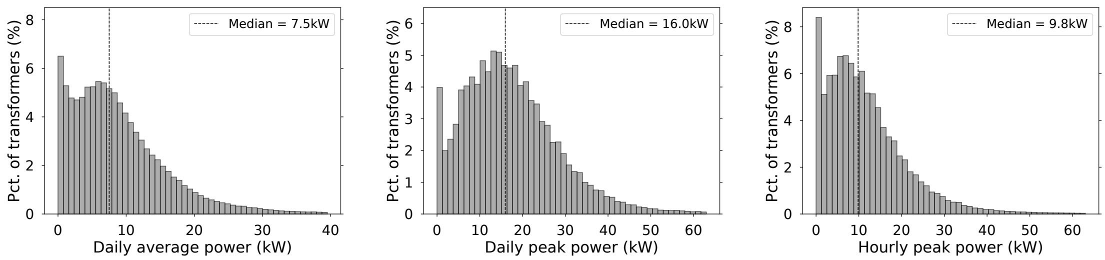
Figure 10(b) depicts the distribution of potential energy reduction for buildings in our dataset. It shows that electric heat pumps can reduce annual energy usage by 1,193 GWh, with a median reduction of 107.5 MWh. Most buildings reduce energy usage by up to 200 MWh, with a few large energy consumers seeing annual reductions of up to 800 MWh, which is 7.5× the median. Reducing energy consumption makes buildings more energy efficient, and this makes electric heat pumps an attractive replacement for gas heating. In addition, the reduced energy consumption can also significantly decrease the utility bills for the households depending on the location, household heat usage patterns, and prices for electricity and natural gas.

7.2 Impact on the Electric Grid

The transition to electric heat pumps from gas-based heating adds significant additional load to the electric grid. This additional load can trigger upgrades that require replacing household meters, service lines, electric transformers, electric distribution lines, and other equipment upstream. We analyze the impact of proposed transition strategies at two levels: (1) additional electricity load added at the household level, (2) additional average and peak load added at the electric transformer level. The first analysis informs the potential upgrades to the household wiring, service meter, and the service lines. The second analysis informs the potential upgrades to the electric transformers and other equipment upgrades upstream.

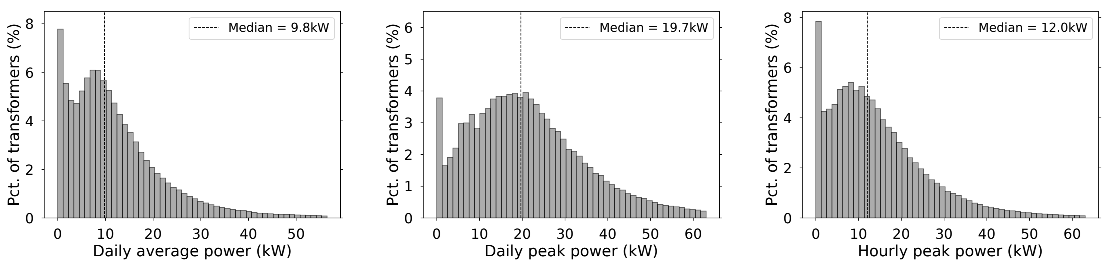
Household-level analysis. To compute the expected electric demand, we estimate the amount of heat energy generated from a building's gas consumption, and compute the electric energy required to generate the equivalent amount of heat energy (details in §5). Figure 10(c) depicts the CDF of electric demand required by heat pumps across the entire system. It shows that the median buildings increases electric demand by ≈ 72 MWh annually. The figure also indicates that most buildings increase electric demand by up to ≈ 200 MWh and only a few buildings having an additional annual demand of > 200 MWh. Finally, the median annual gas energy is 179.1 MWh, which indicates a 60% reduction in absolute energy consumption. Further analysis is needed to study the impact of the extra load on the electric grid. However, these preliminary results show how the grid is expected to change as the penetration of heat pumps increases in buildings.

Transformer-level analysis. While the previous analysis informs household-level increase in the electric load, most homes have over-provisioned electric components and will probably not require any infrastructure upgrades. However, the electric distribution network components, such as transformers, generally operate at or near their peak capacity in most grid locations. As a result, the added load to the households, when aggregated across all connected households, will trigger upgrades at the transformer level. Utilities typically size the distribution transformers, and the edge transformers near households, based on the expected peak load of connected buildings. While the transformers can operate at a higher load than their rated capacity, they generate excessive heat that needs to be absorbed



(a) Average load (daily)
(b) Peak load (daily)
(c) Peak load (hourly)

Fig. 11. *Distribution of (a) average of daily load, (b) peak of daily load, and (c) peak of hourly load exerted on the electric distribution transformers in our dataset before transitioning from gas-based heating to electric heat pumps. The transformer load values on the x-axis are limited to 0-99.5th percentile range.*



(a) Average load (daily)
(b) Peak load (daily)
(c) Peak load (hourly)

Fig. 12. *Distribution of (a) average of daily load, (b) peak of daily load, and (c) peak of hourly load exerted on the electric distribution transformers in our dataset after transitioning 50% of the households from gas-based heating to heat pumps. The transformer load values on the x-axis are limited to 0-99.5th percentile range.*

by the safety mechanisms such as mineral oils. This scenario is highly undesirable as it reduces the efficiency and the lifetime of the transformers. The mineral oil can evaporate at high temperatures, which may lead to melting of transformer coils resulting in power outages. As a result, transformers cannot operate at beyond 125% of their rated capacity for long periods and need to be upgraded.

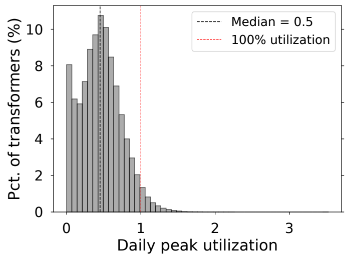
We analyze the impact of transition to heat pumps on transformers over different time scales. To investigate the increase in the sustained usage of the transformer, we analyze the average electric load on the transformer before and after the transition. To investigate the increase in the peak usage of the transformer, we analyze the daily and hourly peak electric load on the transformer before and after the transition. In all scenarios, we set the transition level to 50%, which means that 50% of the homes has been transitioned from gas-based heating to air-source electric heat pumps.

Figure 11(a) and Figure 12(a) show the average of daily load at the transformers connected to households under analysis before and after the transition, respectively. The average daily load at the transformer can be as high as 40kW with a median load of 7.5kW. The average daily load increases significantly after the transition to electric heat pumps. At the high end (99.5th percentile), the daily average load increases to ∼58kW, representing an increase of atleast 45% over the pre-transition daily average load. For the median transformer, the average daily load increases by over 30.66% from 7.5kW to 9.8kW. This high increase in the average daily load suggests that a significant number of transformers may need to be updated if they were operating at, or near, their rated capacities.

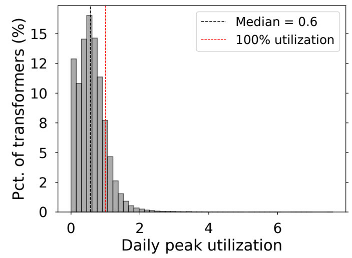
Figure 11(b) and Figure 12(b) show the peak of daily load at the transformers connected to households under analysis before and after the transition, respectively. The daily peak load is almost double than the average daily load, both before and after the transition, suggesting that the transformers are not consistently under a high load. The daily peak load, for the median transformer, increases from 16kW to 20.1kW resulting in an increase of more than 25.6% after the transition. At the high end (99.5th percentile), the transformer has a daily peak load of ∼94kW. This represents an increase of 44.6% over the 65kW peak daily load observed at the highly loaded transformer before the transition. This means that both the average daily load and the peak daily load increase by almost the same amount, ∼46%, after the transition to electric heat pumps.

Finally, Figure 11(c) and Figure 12(c) show the distribution of hourly peak load at the transformers. There are two key observations to be made from the distributions of hourly peak loads and their comparison with daily peak load distributions. First, the hourly peak load for the median transformer increases from 9.7kW to 12kW, an increase of 24%. At the lower end, 20% of the transformers experience a load of 0-5kW both before and after the transition, which means that there is not a significant increase in the load profiles of lightly loaded transformers. The hourly peak load for the 99.5th percentile transformer increases from 48kW to 65kW, an increase of 36%, which means that transformers with high existing load experience the most increase in their load after the transition. This is a concerning outcome for the grid operators as it will necessitate an immediate upgrade of significant number of transformers.

Second, there seems to be a discrepancy between the daily peak load values and the hourly peak load values, hourly peak values are lower than daily peak values for the median transformer. However, the daily peak load cannot be higher than the hourly peak load. This apparent discrepancy stems from the different number of samples



(a) Daily peak utilization



(b) Daily peak utilization at 50% transition

Fig. 13. *Distribution of daily peak utilization for transformers before (a) and after (b) transitioning 50% of the households to electric heat pumps. Utilization here represents the load experiences by the transformer divided by its rated capacity. A value of 1 means that transformer is fully utilized. A value of 2 means that transformer has load twice its rated capacity.*

and resulting bins in both graphs. For example, over one year period, there are 365×24 hourly values and only 365 daily values available for a single transformer. Given the different number of data points, the high end cut-off of 99.5th percentile trims different number of highly loaded transformers, which results in different x-axis lengths. However, the median values are more intuitive to understand as daily peak for median transformer is based on a single value per day, which is the highest of all hourly values, while the median of hourly peak values encompasses multiple lower hourly values.

In our transformer-level load analysis, we discussed that a significant portion of the transformers see a considerable increase in their peak loads and may need an upgrade. To quantify the number of transformers needing an upgrade post transition, we look at the utilization levels for the transformers. The utilization level at the peak is defined as the transformer daily peak load for the transformer in kW divided by its rated capacity in kVA. We assume an ideal power factor of 1, 1kVA is equal to 1kW, which gives us a conservative lower bound on the number of transformers that would need an upgrade. Figure 13 shows the daily peak utilization of the transformers in our dataset before and after transitioning 50% of the households to electric heat pumps. Remember that transformers can tolerate 25% higher peak load than their rated capacity.

In Figure 13(a), we observe that less than 4% of the transformers are overloaded (have a daily peak utilization of 1 or higher), less than 1% of the transformers are in a critical condition (have daily peak utilization of 1.25 or more), and no transformer has a daily peak utilization above 1.4. This suggests that more than 99% of the transformers do not require immediate upgrades. On the other hand, in Figure 13(b), a significant number of transformers have become overloaded after the transition. More than 11% transformers are over loaded (have a daily peak utilization of 1 or higher), ~5% of the transformers are in a critical condition (daily peak utilization of above 1.25), and ~2% of the transformers observe a daily peak utilization of 1.5 or higher. Some of the transformers will need to operate at twice their rated capacity to support the additional electric load of transitioning 50% of the households to heat pumps.

Our analysis of the impact of electric heat pumps on the electric grid suggests that such a transition can significantly burden the electric grid. In addition to the objectives of carbon emissions reductions, carbon efficiency optimization, and targeting inefficient buildings, the transition policies should also consider the potential cost of upgrading the electric grid infrastructure. Such a consideration will favor the choice of households connected to lightly loaded transformers at the start of the transition. The households connected to the overloaded transformers can be transitioned when their transformers reach the end of life or need replacements due to increase in their non-heating electric loads. An intelligent transition strategy can also favor overloading smaller and low cost transformers as opposed to larger and expensive transformers as we reach the high penetration level of electric heat pumps. It is worth noting that the transformer upgrades cannot be avoided, they just need to be pushed farthest into the future so that the electric grid components such as tranformers reach their natural end of life.

7.3 Takeaways for Designing Decarbonization Policy

We next outline the key takeaways, for the design of decarbonization policies using electric heat pumps, from the evaluation of our transition strategies and impact analysis.

First, we have shown that making CO_2 footprint reduction the sole objective of decarbonization has several drawbacks. For instance, when CO_2 footprint is the sole objective of the optimization, the largest homes, which tend to belong to more affluent homeowners, are picked. This is because they tend to be the highest CO_2 emitters. However, since heat pump conversions come with government subsidies, this approach directs most subsidies to higher income households, which may not represent the best outcome for government policy. By considering CO_2 and energy efficiency, inefficient smaller homes as well large emitters would be chosen for transition, which leads to a more balanced transition. Future work could also consider normalizing usage based on occupancy, and this could lead to even more equitable policies.

Second, our results show that older buildings tend to be more energy inefficient, and may benefit more from transition than newer ones. This is due to improved building standards over time, as well as wear and tear in the older building. Consequently, a transition approach should prioritize these buildings more in decarbonization.

Third, we show that transitioning to electric heat pumps have significant potential to reduce CO_2 emission, up to 81%. Therefore, to combat climate change, energy policy must move with haste towards decarbonization pathways such as electric heat pumps.

Finally, we show that the transition to electric heat pumps can significantly reduce the energy consumption and the utility bills for the consumers. Also, the transition can have a significant impact on the electric grid infrastructure, such as transformers. There is a need for targeted transition strategies that consider the cost of the transformer upgrade, its capacity, its current load, and its stranded value, when selecting homes for transition.

8 RELATED WORK

In this section, we discuss prior work on the energy transition, decarbonizing heating in buildings and electric heat pumps.

The energy transition. Multiple studies on transition pathways to a clean energy future have been conducted. Most of these studies examine the economic, environmental and societal benefits of a successful energy transition. For instance, Santamarta et al [33] evaluated the potential of transitioning to geothermal energy showing that in addition to CO_2 emission reduction, 66% energy savings and 13% ROI can be realized. Heinisch et al [16] propose an optimization model that interconnects various sectors of the energy ecosystem i.e. the electric grid, heating requirements and transportation, and heat pumps. Gonzalez-Salazar et al [14] explore pathways to phasing out coal-fired heating stations in favor CO_2-free energy sources. These studies are performed at macro scale i.e. energy generation and CO_2 mitigation are performed from centralized point of view. Our work is complementary to this work as it evaluates the potential of distributed transition at high granularity.

Decarbonizing heating. There have been numerous studies on decarbonizing space heating in the building sector [4, 17, 23, 31, 36]. For instance, Padovani et al [31] quantified the economic and decarbonization implications of replacing propane heating with cleaner electric energy sources such as solar heat pumps. Waite & Modi [36] propose and analyze a dual transition approach. Instead of replacing all existing fossil fuel heating with electric heat pumps, they propose a mix of both energy sources that gradually phases out fossil fuels over time. Leibowicz et al develop an energy system optimization model for decarbonizing residential buildings that incorporates transitioning to greener energy sources, migrating to more energy-efficiency appliances and improving the thermal properties of buildings e.g. through insulation retrofits. Hopkins et al propose transitioning to electric heat pumps for heating buildings. Finally, Baldino et al [4] analyze the cost and decarbonization benefits of hydrogen and renewable electricity as a replacement for heating. Our work is complementary to this work, as we evaluate the impact of multiple building selection strategies on CO_2 reduction. Since transitioning involves shifting energy demand from one system to another i.e. from gas to electric, our work also quantifies the impact of such transition on the electric grid.

Electric heat pumps. The viability of electric heat pumps in place of gas heating in residential buildings has been widely studied [20, 21, 29, 32, 36, 38]. While some studies focussed on the evaluating the performance of heat pumps in extreme temperatures [29, 35], others have analyzed their potential to decarbonize heating at various geographical scales. For instance, Johnshon & Krishnamoorthy [19] analyzed the cost and economic implications of transiting to electric heat pumps, and how it varies across different regions in the entire United States. Zhang et al [38] studied the decarbonization benefits of electric heat pumps using a simulated energy system of an entire city. Other studies [29, 35] have analyzed the applicability of heat pumps especially in extremely low temperatures. Our work is complementary to this work as we evaluate the viability of heat pumps at high granularity using real world data.

Impact of heat pumps on the grid. Multiple prior studies have assessed the impact of heat pumps on the electric grid [9, 25–27, 32]. For example, Navarro-Espinosa and Mancarella [27] use a simulation based study to assess the impact of heat pumps in a suburban low voltage network. Using a simulation study across multiple cities across the US, Deetjen et al [9] quantify the impact of heat pumps from an economic, emission, health and grid impact perspective. Pena-Bello et al [32] evaluate the decarbonization potential of heat pumps and their impact on the grid. They show that to avoid the need to upgrade grid infrastructure with increase in heat pump adoption, thermal retrofits e.g. building insulation will be required. While these studies mostly use simulated data, other studies have used real world data to quantify the impact of heat pumps on the electric grid. Liang et al [25] perform an empirical analysis to quantify the changes in the electric grid at the hourly level after hear pump adoption. Similarly, Love et al [26] use partial data from > 600 heat pumps to quantify the impact of mass uptake of heat pumps on the grid. They show that such adoption leads to increase in evening peak by 14% across the national grid. Our work is complementary to this work in many ways. First, our analysis quantifies impact on the grid at the transformer level. Second, our analysis uses real world energy usage data at high granularity, which makes our observations more generalizable. Lastly, our work evaluates different adoption pathways, and presents energy policy makes with multiple viewpoints from which heat pump adoption can be evaluated.

9 CONCLUSIONS

In this paper, we conducted 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 performed an in-depth analysis of gas consumption in the city and showed that $\approx$ 17 BCF of gas is consumed directly resulting in $\approx$360 GT of CO_2 emission annually. We presented a flexible multi-objective optimization (MOO) framework that optimizes carbon emissions reduction while also maximizing other aspects of the energy transition such as carbon-efficiency and energy inefficiency in buildings. We showed that transitioning to electric heat pumps can cut carbon emissions by up to 81% and energy required for heating by up to 60%. We also showed that optimizing for other aspects such as carbon-efficiency and energy inefficiency introduces tradeoffs with carbon emissions reduction that must be considered in a transition strategy. Finally, we presented preliminary results that examine the expected additional load on the electric grid by transitioning gas to electric heat pumps. We showed that a median building will add an annual energy demand of 71.6 MWh to the electric grid.

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