Equitable Network-Aware Decarbonization of Residential Heating at City Scale

Adam Lechowicz*, Noman Bashir*, John Wamburu^, Mohammad Hajiesmaili*, Prashant Shenoy*
*Manning College of Information and Computer Sciences, University of Massachusetts Amherst
^IBM Research Africa, Nairobi, Kenya

Abstract

- In the U.S., residential energy usage is responsible for about **20% of total yearly GHG emissions**. A big portion of this is due to residential heating.[1]
- Residential heating is important for decarbonization — the world's **colder climates still depend on fossil fuels** such as oil and natural gas to heat homes.
- There is a push to electrify this sector. In this work, we propose a **novel optimization framework** which maximizes the carbon impact of a decarbonization investment by *leveraging knowledge of the electric and natural gas distribution networks*.
- We show that we can achieve up to **55% greater reductions in carbon emissions** by explicitly considering the financial benefits of decommissioning natural gas infrastructure.
- Furthermore, we extend our framework with **equity constraints**, which allow an arbitrary distribution of investment into different neighborhoods or groups (e.g. low vs. high income), without losing carbon benefits.

Motivation

- There is a push towards decarbonizing residential heating by transitioning to energy-efficient heat pumps powered by an increasingly greener and less carbon-intensive electric grid.
- Over the past few years, advances in air source electric heat pump technology have enabled "drop-in replacement" ducted and ductless units with good efficiency, even at ambient temperatures below -15° C.[2]
- Despite great potential in heat pumps, there are still multiple infrastructural considerations to be made in the residential heating transition:
  - The current electric grid in many places does not have enough capacity to accommodate the additional load, so infrastructure upgrades will be necessary. Furthermore, electrification efforts will erode the natural gas customer base over time. Utilities want to play a central role in these efforts in order to phase out the gas distribution network and spread out electric infrastructure upgrades while achieving carbon reduction goals.
- In this work, we explicitly consider the impact of existing natural gas infrastructure, which is mostly underground, often aging, and expensive to maintain. We show that a carbon reduction strategy benefits by factoring in the potential savings that the utility can anticipate with fewer gas lines to maintain.

Data Set

- Our case study uses data from a city scale municipal utility[3] including both electric usage and gas usage. The data set includes information about the topology of the distribution electric network, and we use GIS to infer the location of natural gas infrastructure.

	Number of Meters	Time Interval
Electric Data	13,800	5 minutes
Natural Gas Data	6,445	60 minutes
Duration	1/1/2020 - 12/31/2020	

Table 1: Key characteristics of the data we use in our case study.

key question: given a limited budget, how can we optimize the transition from natural gas → electric home heating to obtain greater carbon savings?

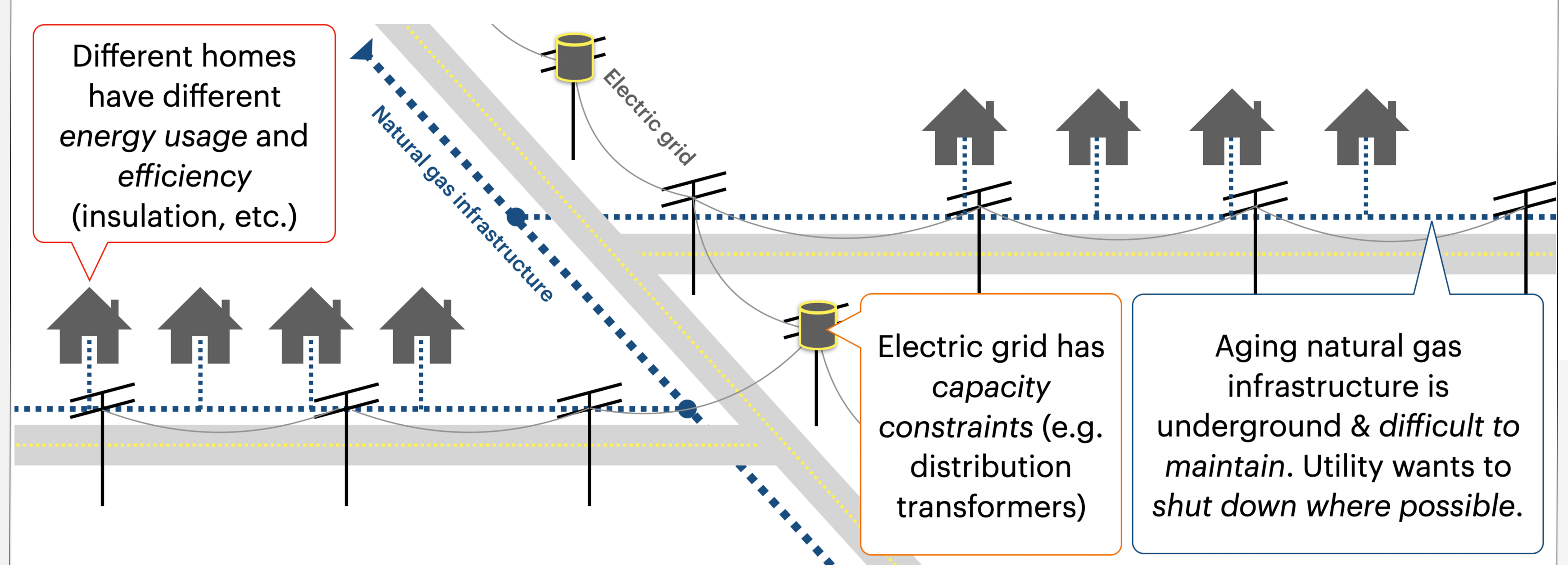

Figure 1: A summary of the residential heating challenge.

Our Approach

- We present a novel **network-aware** optimization framework, which considers the physical topologies of the electric and the gas distribution infrastructure in order to maximize the carbon reduction achieved for a given budget, and enables the decommissioning of more natural gas infrastructure.
- **Variables and Assumptions**. We consider the following quantities associated with the transition for each house in the city:
  - Current usage of natural gas for heating (proxy for carbon emissions)
  - Cost to electrify with a heat pump (estimated based on gas usage)
  - Capacity rating (and cost to upgrade) the distribution transformer serving this house (and other nearby houses)
  - Estimated maintenance cost (yearly) for gas lines in this neighborhood
- We assume that there is a fixed budget B. All expenditures need to fit within this budget.
- In our case study, we also assume that the electric grid is clean, i.e. the carbon emissions from the grid are near-zero. However, the framework can accommodate a grid which is not entirely clean.

Figure 3: Objective and constraints of our network-aware optimization

$$\max \sum_{j \in \mathcal{H}_C} E^{CO_2} g(j), \quad \triangleright \textit{carbon emissions reduction}$$

$$\text{s. t.,} \sum_{j \in \mathcal{H}_C} p(j) + \sum_{i \in \mathcal{T}_C} r(i) - \sum_{(u,v) \in \mathcal{E}_C} m(u,v) \leq B.$$

Cost to install ASHP in chosen houses
Cost to upgrade distribution grid
Savings from decommissioned gas lines
Fixed budget B

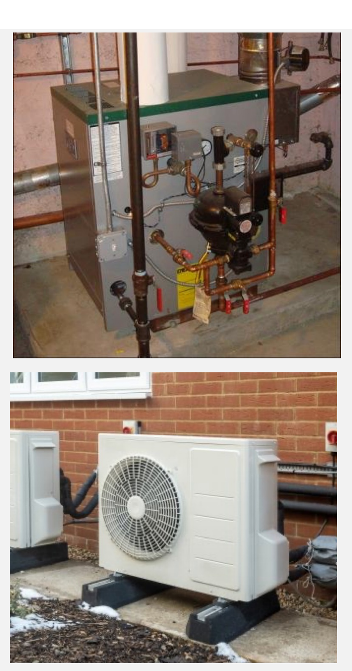

Figure 2: typical natural gas boiler (top) and typical ductless air source electric heat pump (bottom). (U.S. DOE)

References

1. Goldstein et al. (2020) *The carbon footprint of household energy use in the United States.*
2. Schoenbauer et al. (2016) *Field Assessment of Cold Climate Air Source Heat Pumps.*
3. Holyoke Gas & Electric. (2021) *119th Annual Report of the City of Holyoke Gas & Electric Department.*
4. Wamburu et al. (2022) *Data-Driven Decarbonization of Residential Heating Systems: An Equity Perspective.*

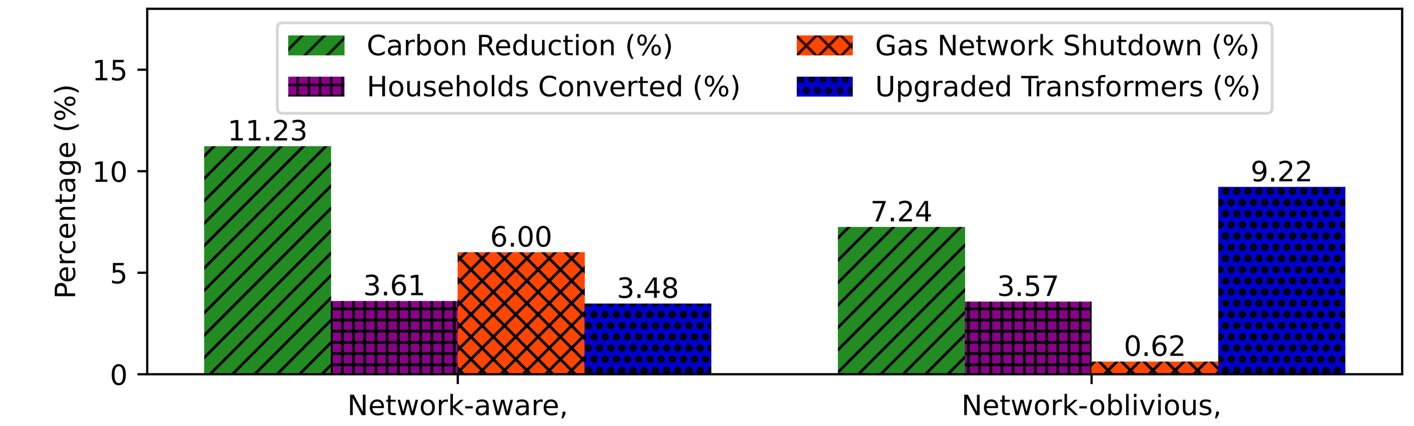

Figure 4: Comparing our network-aware approach with a standard approach proposed in prior work[4].

Equity Concerns

- Equity is an important consideration in this work. Prior work[4] has shown that a strategy which *does not explicitly consider equity* may **disproportionately** choose to target residential heating upgrades towards houses and neighborhoods which are **socioeconomically advantaged.**
- In our work, we propose a configurable **equity constraint**, which can divide the possible transition neighborhoods into several different groups of interest, and distribute investment in an equitable manner amongst these groups.
- In our case study, we use **census data** to split the city into three groups based on median income (i.e. low, middle, high), and show that *without the equity constraint*, the investment is inequitable. Our constraint serves as a mechanism to *explicitly alter this distribution in an equitable manner*.

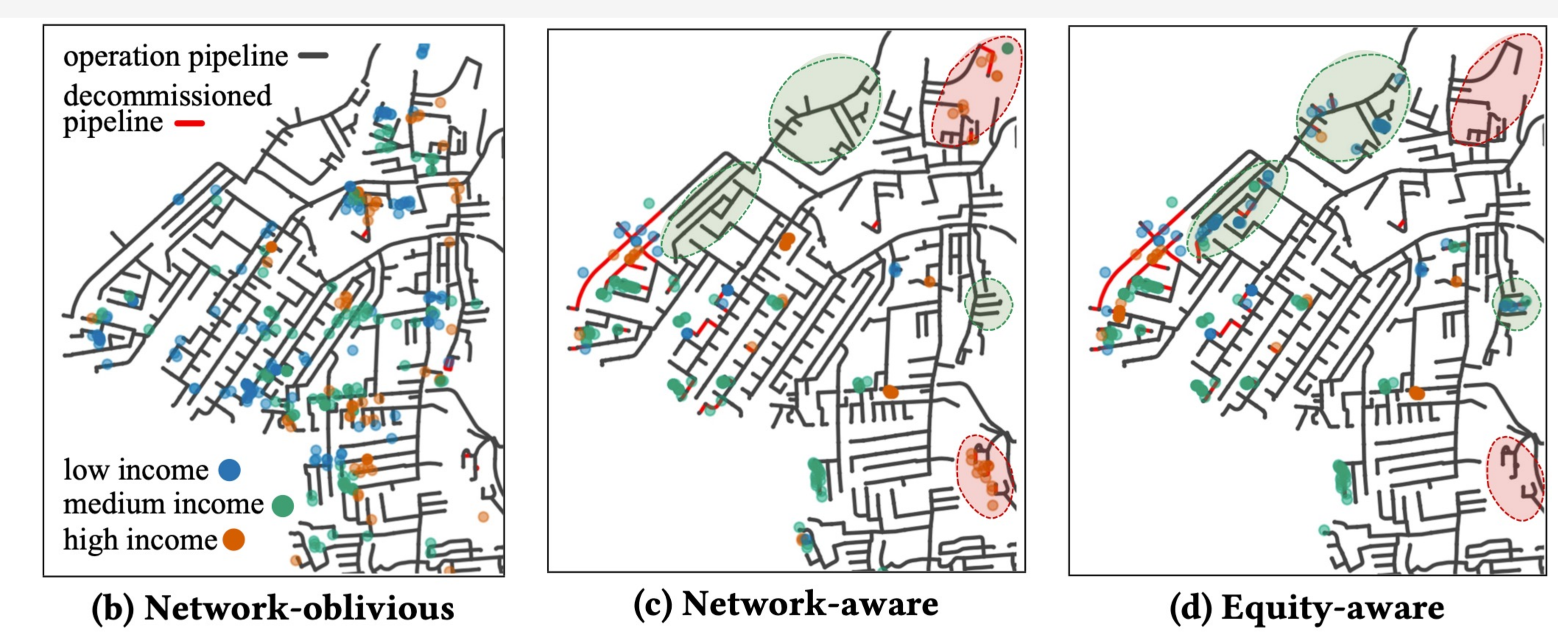

Figure 5: Representative snapshots of each transition strategy. Dots are electrified houses, and red lines are decommissioned pipelines.

Results

- Our results show that by considering the potential savings from decommissioning natural gas infrastructure, we can obtain 55% more carbon reductions over an existing "network oblivious" technique.
- Furthermore, our equity constraints significantly improve the distribution of investment between low, medium and high-income neighborhoods, without losing the benefits of the network aware optimization.

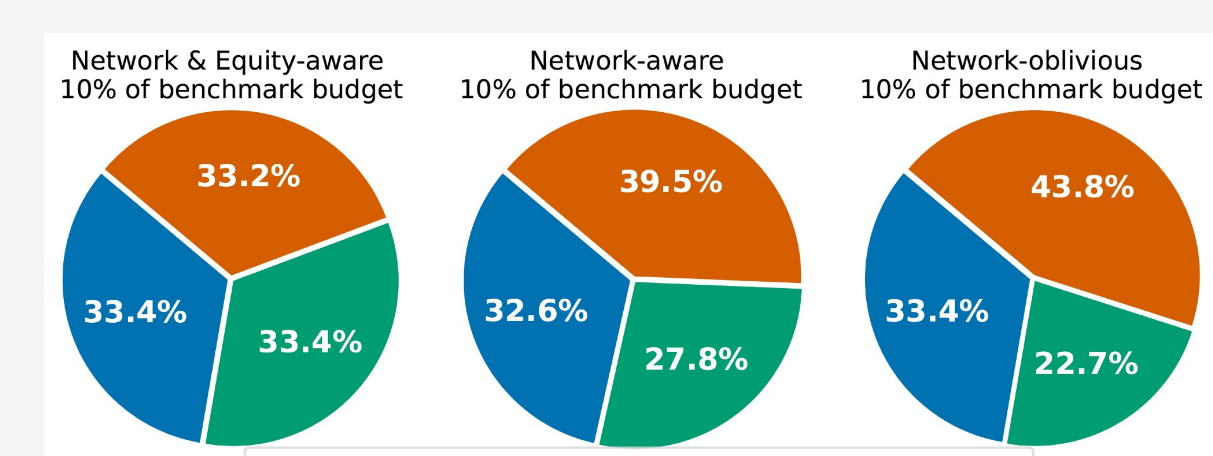

Figure 6: Case study investments in different income neighborhoods, showing disparity in techniques which do not consider equity.

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