Modeling the Implications of Fugitive Gas Emissions on Building Heat Upgrade Decisions

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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***Abstract*— The majority of US buildings use natural gas for heating even though it is a potent greenhouse gas that relies on a leaking infrastructure with significant life cycle fugitive emissions. Recent developments in all-electric heating alternatives or 'certified' or 'renewable' gas alternatives have made decision making about operating building heating systems more complex given quickly evolving emissions and economic profiles. Here, a novel modeling tool was developed to help provide engineers with full cost-accounting of both the economic and greenhouse gas emissions associated with different heating options. The tool is based on the University of Virginia's model for estimating costs and emissions associated with capital expenditures and it was updated with location specific fugitive emissions and cost estimates. Users can input various different common options for heating systems to understand how much of an impact each will have on economic factors such as return on investment, estimated lifetime cost as well as full-cost lifecycle impacts including carbon dioxide equivalents avoided per year, and lifecycle greenhouse gas emissions. The analysis suggests that in most cases it is economically and environmentally preferable to replace gas infrastructure with a heat pump once fugitive emissions are considered. In support of the University of Virginia's net-zero emissions targets, the tool was used to assess several hypothetical heating upgrade projects on grounds including one for Carr's Hill. The tool contains fugitive emissions data for all the major metropolitan areas in the United States and can be easily adopted for use in other locations to provide first-of-its kind information for building managers.**

I. INTRODUCTION

A. Net Zero Building, Decarbonizing Heating

As institutions increasingly set net-zero carbon emissions targets to mitigate their climate impact, there is a growing need for decision support tools that help engineers understand the financial and environmental impacts of capital projects. For building managers and engineers, the decision-making process around building heat delivery is particularly challenging. Buildings are responsible for almost 30% of global emissions, much of this coming from space heating and, to a lesser extent, cooling [1]. To limit global warming to below 2 degrees Celsius by the end of this century, it will be necessary to slash carbon dioxide emissions by mid-century [2]. In 2016, the 7.5 gigatons of carbon dioxide emissions from the heating sector accounted for 21% of global emissions [2]. Most of these emissions come from the heavy reliance on fossil fuels to deliver heating in most buildings. Combustion of fossil fuels is still the most inexpensive way to deliver heat in most building contexts.

B. Leaky Infrastructure

Gas is the most common fuel used for heating buildings in many regions of the United States. Natural gas production is concentrated in certain regions of the country and is collected, transported, and distributed through a vast underground pipeline network. This network contains leaks and some regions and some components of infrastructure leak at much higher rates than others. Natural gas leaks consist primarily of methane, which is a potent greenhouse gas. Methane has a Global Warming Potential (GWP) that is 32 times higher than carbon dioxide over a 100-year time horizon [3]. That means that every kilogram of methane that leaks from our gas infrastructure has, on average, the warming impact of 42 kilograms of CO_2. Not only does leakage have a significant warming impact, it is also costly. A 2018 study by the Rhodium Group found that the global oil and gas industries allow as much as 3.6 trillion cubic feet of natural gas leaks into the atmosphere every year, a leakage rate that correlates with at least $30 billion in lost revenues [4]. These costs are often passed on to distribution companies and end users and are incorporated directly into gas prices. A 2020 project by Mason Inman of the Global Energy Monitor nonprofit studied leaks in the natural gas infrastructure for dozens of U.S. cities and found that almost all of them were leaking methane, and some at staggering amounts. Such information, when reported accurately can have enormous effects on the lifetime emissions of capital projects given their geographic location. Fugitive emissions are not currently considered in terms of individual infrastructure decisions, because they currently only affect emission numbers, which are not required to be disclosed and are not currently priced [5].

C. Heating Options

Even though gas boilers are the most common existing form of heating in US building, there are emerging alternatives on the market. Electric heat pumps operate much like air conditioning units, moving heat against a thermal gradient. In the summer they can cool a space and, in the winter, they run in reverse and heat the same space. From an energy perspective, heat pumps are more efficient than fossil fuel heat sources per unit energy as heat pumps are capable of harnessing ambient heat from their environments [6]. The electricity that they use to operate comes from an electric grid that is rapidly decarbonizing as more wind and solar resources come online. As a result, electric heat pumps can deliver average emissions reductions of 53-67% for 20-year GWP and 44-60% for 100-year GWP compared to natural gas furnaces [7]. Despite the increase in efficiency and decrease in GHG emissions, there is still a level of uncertainty regarding whether the production of the energy used in heat pumps has higher system-wide emissions than some of the most efficient gas furnaces [8]. So, many building owners or operators lack the information needed to decide about upgrading to heat pumps and have instead turned to options like renewable natural gas and certified natural gas as a way to cut emissions [8].

A. Certified and Renewable Natural Gas

Certified natural gas and renewable natural gas are two new options for reducing emissions being promoted by the US natural gas industry. Certified Natural Gas (CNG) is conventional fossil gas that receives certification from a third-party entity ensuring responsible practices in minimizing production and transmission (fugitive) emissions [9]. The gradual adoption of CNG could reduce some of the infrastructure leakage that is widespread today. In contrast, Renewable Natural Gas (RNG) uses biogenic sources from agriculture or landfills to produce methane and feed it into the existing fossil gas infrastructure [10]. RNG avoids a significant source of emissions that would come from these sources were it not captured and generates a usable fuel. These two alternatives both offer a better "promise" than regular natural gas, but still fail to eliminate the emissions that come from burning natural gas. Both CNG and RNG will be offered by the industry at higher prices and preliminary estimates are that RNG will cost up to twice as much as traditional natural gas at best [11].

B. Our Work

The goal of this project was to develop a model that takes a typical financial and emission life cycle assessment (LCA) and adds in location-based fugitive emissions to understand the decarbonization of the electric grid and the addition of a cost on carbon. For simplicity's sake, the model sticks with one consistent efficiency for the heat pump option and offers financial and emissions comparison to the current alternative (a natural gas furnace). This model can be easily adjusted to different efficiency heat pumps, different material, labor, and utility costs, and different policy futures.

II. Methods

Our model is built using the University of Virginia Life Cycle Cost Calculator, an existing financial and emission estimate tool used by engineers to inform capital investment decisions. The excel-based model considers utilities data, labor and materials estimates, and calculates lifecycle costs and emissions values for different types of infrastructure systems. In our analysis, we considered an existing natural gas furnace and the cost and emissions implications of continuing to operate it using CNG/RNG or replacing it with an electric heat pump. The new model we developed outputs financial and emissions information (including fugitive emissions) for the next 20-30 years so that the user can see how quickly and effectively emissions are reduced by the two systems based on the different scenarios we developed.

The scenarios we considered are: Business as Usual (BAU); BAU including Fugitive Emissions; CNG without Fugitive Emissions; RNG without Fugitive Emissions; CNG plus Fugitive Emissions; and RNG plus Fugitive Emissions. All six of these scenarios can be tested for building decisions in any region of the United States as different regions have different fugitive emissions profiles, decarbonization schedules for the electric grid, and input and materials costs. The model considers how prices of electricity and natural gas (including CNG and RNG) are expected to change in the coming years. Based on literature review and UVA estimates, the expected trends in the energy industry and other constant trends like inflation, an escalation figure was determined to project utility costs. The 20–30-year projection allows users to analyze when their breakeven point would be for each of these scenarios, further informing whether, and when, they should update their infrastructure.

A. Business-as-Usual (Base Case)

The Business-as-Usual case uses the original UVA Model's estimating process of taking user inputs on labor, material, and usage estimates for different systems and reporting separate emission and net present value numbers. While this approach does consider the emissions profiles of gas boilers and heat pumps, it does not quantify the impacts of unmeasured leaks in gas transmissions.

B. Business as Usual Plus Fugitive Emissions

Developed in likeness to The Gas Index Model 2020, in which fugitive methane in a number of U.S. cities was analyzed through upstream production and distribution processes to produce a city-wide leakage estimate, our model estimates location-based fugitive emissions in a specified city for a given project. Using a similar approach of collecting data from EIA and PHMSA sources, we were able to calculate fugitive emissions in six categories: production, transmission, distribution mains, distribution services, gas meters, and building leaks. To attain a leakage percentage for each city, we summed the leakages for each component and divided by the total consumption for that city. This calculation was then extrapolated to our life-cycle cost accounting tool to create a fugitive emissions estimate that is geographically explicit and can paint a more accurate picture of these infrastructure decisions [12]. On the inputs tab of our model, a dropdown menu was added for the user to select their city, which would then input the leakage rate into the emissions factor for natural gas, adjusted for the GWP of methane.

C. CNG without Fugitive Emissions

This case captures the emissions profile for certified natural gas, an alternative emissions profile in fugitive emissions are curtailed by the gas industry. In this model, the pricing change is reflected immediately (from a user input that asks the current premium to upgrade to CNG) and inflated at the chosen rate for natural gas, but emissions are treated as a gradual change – in more specific terms, the emissions factor for natural gas is altered to reach an eventual emission reduction of 4% by 2032 (year 10 in the model) through an exponential decay formula. Given the uncertainty with CNG emissions trajectories, building owners would be reporting a 4% reduction on an inadequate sum of emissions.

D. RNG without Fugitive Emissions

RNG is fundamentally different than CNG in that it produces a biogenic product that is then transmitted in the same pipeline that regular fossil gas would be. In our model, the cost is reflected in the same manner (through user input) as the third scenario, but instead of formulaically decreasing the emissions factor, it is decreased at estimated rates released by UVA – piecewise-linearly reaching 0.0040 by 2030, -0.0599 by 2040, and -0.1117 by 2050 (with negative emissions based on carbon credits). This case does not include the “full picture” of a building’s emissions without the consideration of fugitive emissions, especially since RNG is transmitted in these same leaky pipes as fossil gas.

E. CNG plus Fugitive Emissions and RNG plus Fugitive Emissions

These scenarios both take the previous models and adjust the starting emissions rate to one that includes gas leakages through the process described in Section II.B.

Overall, our ideal use for these models is for a building owner to consider scenarios 2, 5, and 6, all of which include fugitive emissions. As the United States raises its standards for emissions reporting and begins to look at carbon pricing and the decarbonization of the electric grid, these models give a user much more of an understanding of their whole lifecycle emissions and the costs associated with them.

III. Model Development

A. Fugitive Emissions

To calculate the fugitive emissions numbers used in the model, the following formula was used:

$$P + T + Ma + S + Me + B = \text{Total Fugitive Methane Leakage in City (Mcf)}. \quad (1)$$

Where

P = City Consumption (Mcf) * Production Area Leakage Rate (%),

T = City Consumption (Mcf) * Transmission Distance (miles) * Transmission Leakage Rate (% / mile),

Ma = Material of City Mains (miles) * Leaks per Mile of Material (# / mile) * Methane per Leak of Material (Mcf / # / mile),

S = Material of City Service Lines (miles) * Methane per Leak of Material (Mcf / # mile),

Me = City Consumption by End Use (Mcf) * Meter Leakage Rate by End Use (%), and

B = City Consumption by End Use (Mcf) * Building Leakage Rate by End Use (%).

B. Electric Power Grid Emissions Profile

The Electric Power Grid Emissions Profile has a large effect on the results of our model. If a building facing a potential infrastructure update is under a system set to decarbonize by a certain year, the system can be updated by changing the emission factor of electricity at the following rate:

$$E_f(i) = E_f(i-1) - [E_f(i-1) - E_f(n)] * [i / (n-i)]. \quad (2)$$

Where

$E_f(i)$ = the electricity emission factor in year I, and n = the year where the grid reaches zero emissions (starting from year 0).

This can be adjusted in any one of the scenarios, depending on user preference (with specific directions for cell adjustment provided on the cover page).

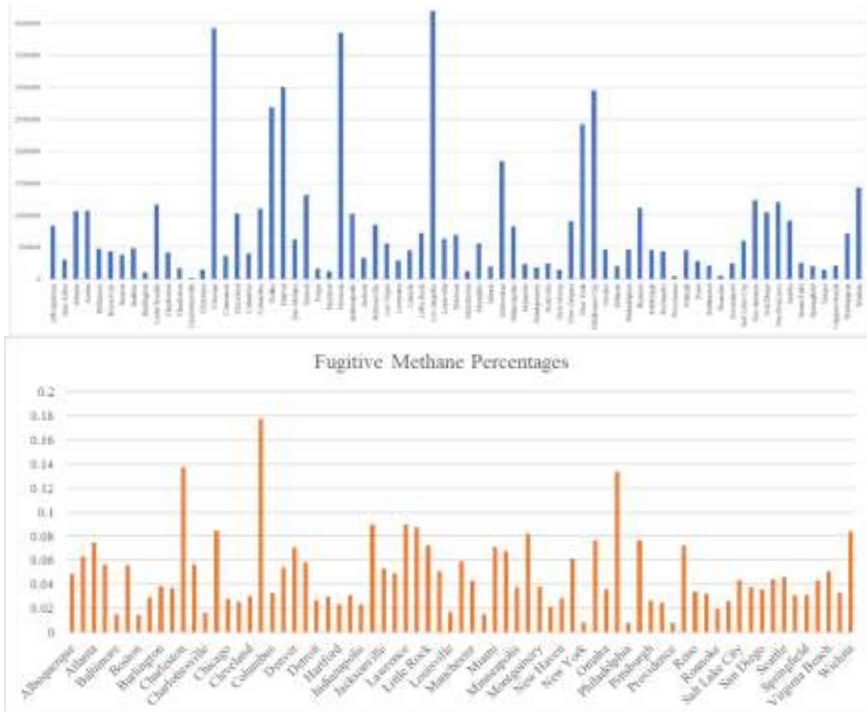
IV. Analysis of Results

The resulting tool simplifies the ability of building owners to consider both emissions and economic factors, when considering capital upgrade projects. The model results are sensitive to a variety of inputs including building location, utility usage and costs, labor and material costs, and how much building owners hope to consider policy aspects like decarbonization of the grid and carbon pricing. The core model will allow building owners and managers to obtain more accurate lifetime cost and emission estimates for large scale electrification. Contemporary life cycle cost and emissions analysis tools have yet to incorporate fugitive methane emissions from upstream sources and therefore do not accurately demonstrate the full effect of infrastructure decisions. *Analysis of Variables*

A. Fugitive Emissions

As would be expected from varying infrastructure city-to-city, some areas have a much higher effect of including fugitive emissions in the model. For example, while Los Angeles, CA has the highest total leakage in Mcf, it is a fraction of the rate of leakage that occurs in Columbia, SC on a per consumption basis (See Figure 1). So, the difference between scenarios one and two when a carbon cost is added in would be much greater if a project were to occur in Columbia than in California. Our hope is that in areas with much higher leakage rates, project managers will be more likely to revert to electrification because of emissions (and potential financial) implications of their leaky infrastructure.

Figure 1 Leakage Values and Rates by City on a Per-Consumption Basis



B. Decarbonization of Electric Grid

Adjusting this variable at a dynamic rate instead of a set rate allows a user to better understand how their emissions may decrease in an electric system at a faster rate than in a natural gas system that decreases in emission factor (such as switching to RNG in a natural gas furnace system). If a cost of carbon is tested on an accelerated decarbonization timeline, it multiplies the effect of decreasing emissions in an electric system on the lifetime value, making a consumer more likely to adopt an electric heat pump over a natural gas system or gas alternatives. This result depends heavily on the timeline of decarbonization chosen by the institution or user.

C. Cost of Carbon

The cost of carbon is an important variable in our model. Today there is no federal price on carbon in the United States, though some regions do price it, such as California. The value of including a carbon price in our model is that it integrates the two sides of the model – the environmental side and the economic side. In any given case, a consumer can easily calculate the breakeven cost of carbon that would make them choose an electric system over a gas furnace. Without an actual cost on carbon or any changes to the pricing of natural gas or material inputs, it's hard to convince a user that electrification will always be economical, so we can model potential costs. As mentioned before, it will always depend on the user inputs case-to-case. But at a certain point in each case, there is this breakeven cost of carbon that would convince users to invest in a new, cleaner system.

Case Study

To evaluate our tool, we looked at the case of the Carr's Hill Building on the University of Virginia grounds to show the difference that certain variables make on the output decision of this model. This building has one natural gas boiler, and is in Charlottesville, Virginia. The only data we pulled directly from this building are its location and heat use (156.66 MMBtu/Year) [13]. We used that value to calculate the amount of natural gas that would be used in system one (a gas furnace) and the amount of electricity needed to generate the same amount of heat in system two (an electric heat pump) based on efficiency values. The other input values were assumed based on our analysis. The replacement cost of a natural gas boiler was set at $60,000, based on estimates from RSMeans utility database [14], with an expected life of 25 years. The electric heat pump in this study will cost $100,000 in upfront capex, and the same replacement cost, with an expected life of 15 years. The efficiency values (coefficients of performance) for the furnace and heat pump were chosen as 0.93 and 0.75, based on national averages [15].

When the breakeven cost of carbon (the cost that makes both lifetime values equal) that would support a switch from a natural gas to a renewable system is taken into account, we can further see the disparities and uncertainties that these decisions bring. In the "Business as Usual" model, where fugitive emissions are ignored, that cost is

$49/MtCO$_2$e, whereas it drops to $42 when fugitive emissions are included in the next scenario. The vast difference between these numbers shows how important it is to consider these factors when reviewing potential policy futures – if methane leakages are required to be reported, it's financially much smarter to switch to an electric system in the event of any carbon pricing.

When considering the use of CNG or RNG for a furnace versus electrification in each case, there is a much larger difference in model recommendations. The breakeven cost of carbon for CNG and RNG (fugitive emissions considered) are $43 and $131, respectively. This massive difference is due mostly to the assumptions on emissions coefficients (supplied by UVA) used in the model. Now, renewable natural gas and anaerobic digestion is a relatively new technology, so these emissions profiles of these technologies are speculative, which is one of the reasons the model favors keeping a natural gas system over an electric system.

Our model was used to identify a breakeven point in terms of timing (with a set cost of carbon), rather than looking at net present cost. Below are two graphs, one that displays the costs and emissions of the two systems with no carbon tax, and another that displays them with a $10 carbon tax (See Figures 2 and 3). With the $10 carbon tax, the two systems break even around year 26. As a result of this case study, there are two decisions that would likely be made, depending on the goals of the project. If the only goal were to choose the cheapest option regardless of policy scenarios, the project manager would likely choose to invest in renewable natural gas. However, there are always outside factors to be considered. For example, maintaining the status quo of a natural gas system will likely not get UVA to its goal of net zero emissions by 2050, and doesn't give it the flexibility to adapt to potential carbon pricing in the future.

Figure 2 Electric Heat Pump versus Gas Furnace Cost and Emissions, Base Case

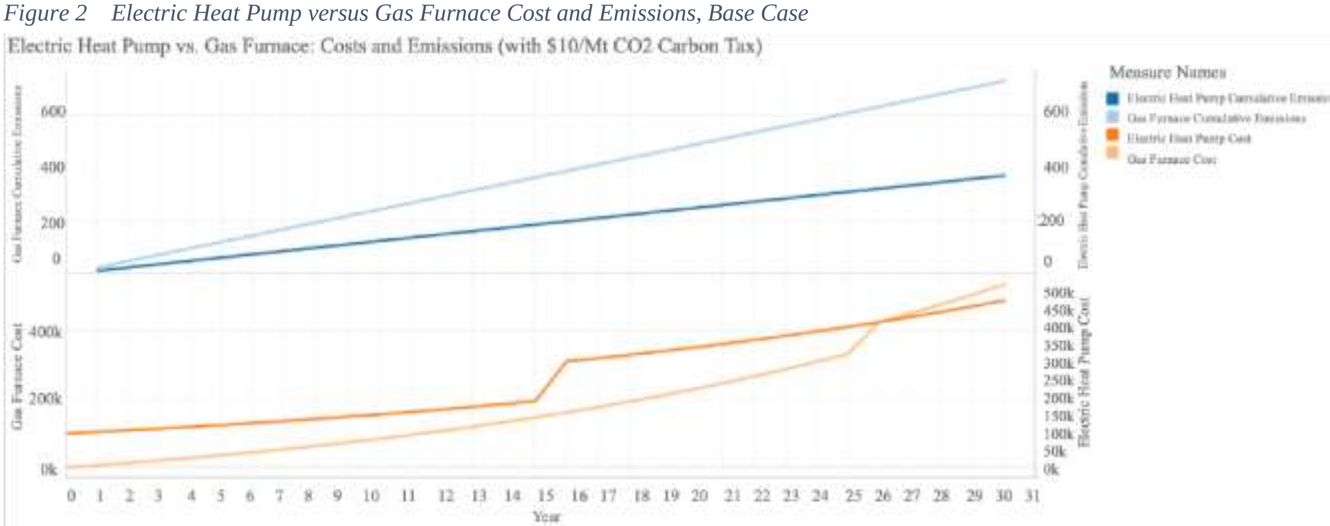
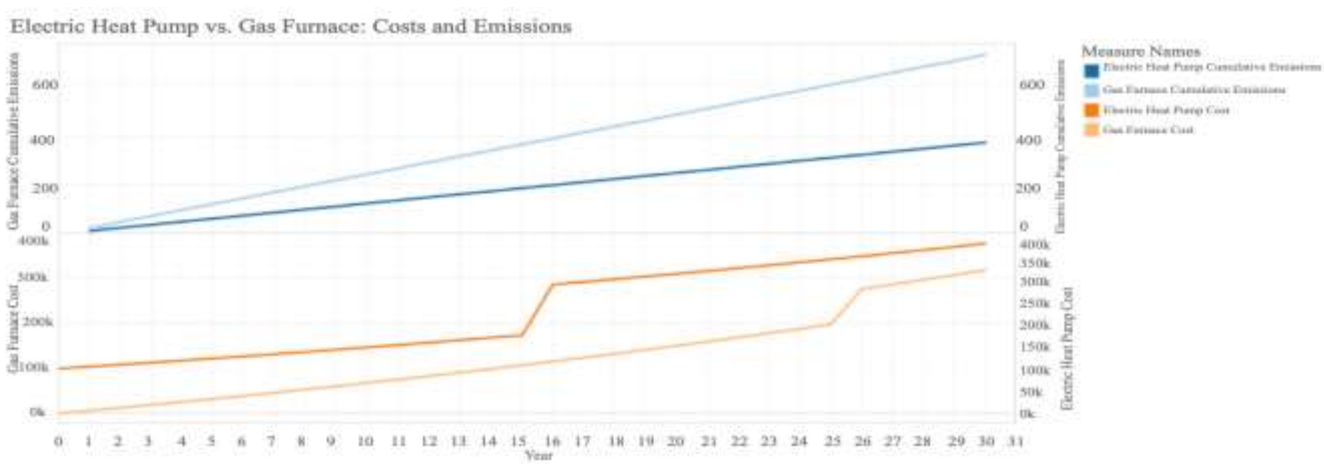


Figure 3 Electric Heat Pump versus Gas Furnace Cost and Emissions, $10 Cost of Carbon



V. Conclusion

We developed a model that takes user inputs on a building infrastructure update decision and displays different cost and emission scenarios so all factors can be considered. The user can consider not only their input costs, but also the effect on the decision of future policy changes like a cost on carbon or an accelerated decarbonization of the electric grid. Throughout the development process, we've seen over and over again that there is never a homogenous solution when it comes to tackling emissions and climate change. The calculations and assumptions we made were based on a combination of literature review, conversations with experts in the field and potential users, and some informed estimates. Overall, this model will allow project managers to consider all factors beyond just upfront costs, and give them the flexibility to investigate different outcomes. It is an adaptable model and can be updated along with the progress of climate action. Ideally, this can become a live model that takes inputs from an API so users can make informed decisions in real time without the assistance of an expert.

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