GHG policy impacts for Seattle's buildings: targets, timing, and scope

TRAVIS WALTER [ID]

PAUL MATHEW [ID]

Author affiliations can be found in the back matter of this article

ABSTRACT

Many US cities are addressing climate change by setting goals to reduce their greenhouse gas (GHG) emissions by a specified amount within a specified time period. In order to achieve these goals, reducing emissions from existing buildings is crucial. Many cities are passing legislation to target existing buildings through benchmarking, auditing, retuning, or energy or emissions performance standards. As cities design legislation, they must consider the timing of the policies, how to prioritize building types and sizes, and how these design decisions will impact the city's emissions. This paper addresses these questions for one particular US city: Seattle, Washington. A model of Seattle's building stock was created with benchmarking and tax assessor data. It was then used to predict GHG emissions reductions due to different policy implementations for existing commercial and multifamily buildings. Key findings are: (1) the proposed emissions policy is expected to reduce cumulative emissions from buildings by 19% between 2020 and 2050; (2) delaying the implementation of the policy by five years could limit savings to 12%; and (3) including smaller buildings in the policy could increase savings to 34%. The lessons learned and how this can be used by other cities are discussed.

POLICY RELEVANCE

As cities design legislation for energy performance standards, they must consider the impact that the timing of policies, prioritization of building types and sizes, and electrification will have on the city's GHG emissions. A new process is presented that can assist policymakers to understand the impacts of policy decisions on decarbonizing the building stock. A model of Seattle's building stock was created to predict emissions reductions due to different policy implementation scenarios. This model shows the impact of Seattle's proposed emissions policy. The current policy is expected to reduce cumulative emissions from buildings by 19% between 2020 and 2050. If the implementation of the policy is delayed by five years, then cumulative emissions savings would be reduced to 12%. The inclusion of smaller buildings in the policy could increase cumulative emissions savings to 34%. Other cities can use this process to better understand their proposed policies for their building stock.

1. INTRODUCTION

Many cities across the world have set goals to reduce their greenhouse gas (GHG) emissions. For example, the C40 Cities network includes over 90 of the world's largest cities that have committed to meeting the goals of the Paris Agreement (C40 Cities n.d.). While climate change policymakers have traditionally emphasized supply-side measures for climate change mitigation, there is a growing recognition of the importance of, and potential for, demand-side mitigation measures in all sectors (Creutzig *et al.* 2018).

In most US cities, the building sector is typically the largest contributor to a city's total GHG emissions. For example, buildings account for almost 70% of New York City's total GHG emissions, and more than 90% of the current buildings will still exist in 2050 (City of New York 2018). Cities have developed an array of demand-side policies and programs to address this. In new construction and major renovation, the focus has generally been on energy efficiency codes and standards such as ASHRAE 90.1 (ASHRAE 2019) and the International Energy Conservation Code (IECC) (ICC 2018).

However, new construction accounts for just 1% of floor space per year in the US (EIA 2020). Meanwhile, 44% of the non-residential building stock and 67% of the residential stock in 2050 will be in buildings that were built in 2019 or earlier (Unger & Nadel 2019). Existing buildings are critical to address total emissions, but are generally much harder to address with codes and standards due to the wide range of construction practices over different building vintages.

In the US, the primary policy mechanism to date for existing buildings has been energy benchmarking and disclosure. Some cities also have requirements for energy audits or building tune-ups. While benchmarking and audits do not inherently require energy-use reductions in and of themselves, the premise is that requiring information disclosure will prompt action by building owners and operators, as evidenced by some studies (Meng *et al.* 2017; Palmer & Walls 2017; Kim & Lim 2018; Gui & Gou 2020). A study of New York City's mandatory audit policy found reductions of 2.5% for multifamily and 4.9% for office buildings, suggesting that audits create an insufficient incentive to invest in energy efficiency at the level needed to meet the city's GHG reduction goals (Kontokosta *et al.* 2020).

Recognizing that benchmarking, audits, and voluntary programs are not aggressive enough to meet climate goals, several cities and states have passed mandatory building performance standards (BPS) for existing buildings, requiring buildings to meet a particular level of energy or GHG performance (Nadel & Hinge 2020). As cities look to design and implement these policies, they have to address details such as what metric to use, the level of performance, the phasing and timing for different building types and sizes, *etc.* Building owners, operators, advocacy groups, and other stakeholders have a strong interest in these details and cities need to evaluate the impacts of these aspects to inform the rulemaking process. This article presents the results of a BPS planning effort for the City of Seattle. The approach and insights may also offer useful information for other cities considering BPS mandates.

2. SEATTLE'S POLICY FRAMEWORK

Seattle adopted a Climate Action Plan in 2013 that set a goal of zero net GHG emissions in the road transportation, buildings, and waste sectors by 2050 (Office of Sustainability & Environment 2013). In 2018, the city council also adopted a resolution affirming Seattle's commitment to the 1.5°C goal established in the United Nations' Paris Agreement, and the mayor issued a Climate Action Strategy outlining 12 key actions to remain on track (City of Seattle 2018). The buildings sector accounts for about a third of total emissions for the city. This is a relatively lower percentage compared with other cities because Seattle's electricity supply has very low GHG intensity by virtue of hydroelectric generation.

Seattle's Climate Action Plan projected building energy emissions to reduce by 39% by 2030 and by 82% by 2050 relative to a 2008 baseline. The plan identified several near-term (by 2015) and longer term (by 2030) actions, broadly falling into four categories: information (*e.g.* energy

disclosure), performance requirements, incentives, and energy supply. Two key long-term action plans are relevant to existing buildings:

- creating a minimum performance standard for the entire stock
- requiring periodic retro-commissioning (building tune-ups) for the largest and least efficient commercial and multifamily buildings

The 2018 Climate Action Strategy reaffirmed performance standards as a key action for commercial and multifamily buildings.

Seattle adopted a building tune-ups requirement in 2016, applying to commercial buildings >50k ft^2 (4645 m^2) (Office of Sustainability & Environment n.d. a). The tune-ups target low- and no-cost actions related to building operations and maintenance. Several studies have shown that savings from building commissioning can yield savings in the range of 5–15%, with simple paybacks of 0.8–3.5 years (Crowe *et al.* 2020; Mills 2011; Mills & Mathew 2014).

In 2019, Washington State (in which Seattle is located) passed a law setting an energy performance standard (WA EPS) for existing non-residential buildings >50k ft^2 (4645 m^2) (Washington State n.d.). It is based on site energy-use intensity (EUI) and uses ASHRAE's Standard 100 (ASHRAE 2018) as a model. The legislation calls for the performance targets to be defined by rule, but to be no greater than the average EUI by building type.

Seattle is now in the process of developing a GHG emissions-based BPS for existing buildings, toward meeting the goals of its Climate Action Plan of net zero GHG emissions by 2050. In designing this BPS, Seattle's planners needed to consider several questions:

- To what extent do existing requirements, that is, tune-ups and WA EPS, meet the 2050 goals and what is the shortfall?
- The current WA EPS requirements are limited to buildings >50k ft^2 (4645 m^2). What is the impact of including smaller buildings in the emissions standards?
- How does the timing of the requirement affect total cumulative GHG emissions between now and 2050?
- What is the impact of building electrification?
- What is the impact of exempting selected building types?

A range of empirical approaches are needed to analyze existing building performance at the building and stock levels (Geraldi & Ghisi 2020). Various organizations have developed stock-level GHG-reduction pathways using top-down approaches (*e.g.* Architecture 2030 2014; CRREM n.d.). These typically involve looking at total sector emissions and then setting a reduction rate or target to define a pathway. While such approaches are effective for characterizing sector level goals and pathways, they are not as effective at addressing more specific policy questions such as those Seattle identified. Addressing these questions required a more fine-grained stock analysis that accounts for the interaction of different policies, their timing and sectoral scope. At the other end of the spectrum, bottom-up stock modeling approaches have been used to account for the heterogeneity in building technology and end-use characteristics (Langevin *et al.* 2019; Nägeli *et al.* 2020; Brøgger & Wittchen 2018). Such approaches are more complex and require more detailed building-level characteristics and end-use data. In this article we present the results of an empirical analysis to inform Seattle's policy questions. In particular, we leveraged the city's most recent benchmarking data (Office of Sustainability & Environment n.d. b), which provides actual measured data for individual buildings, but without any additional information on building asset and operational characteristics. We worked closely with city officials to define the analysis questions, develop the analysis approach, and review the results.

Throughout this article, floor areas are referred to in units of thousands of square feet because both the current WA EPS policy and the City of Seattle's planned legislation will be defined in those units. To maintain clarity, we use the 'k' suffix to indicate thousands (*e.g.* 50,000 = 50k), as well as in ranges (*e.g.* 50k–90k). The floor areas relevant to Seattle's policy planning (and their metric equivalents) are as follows: 20k ft^2 (1858 m^2), 50k ft^2 (4645 m^2), 90k ft^2 (8361 m^2), and 220k ft^2 (20,438 m^2).

3. POLICY SCENARIOS

In order to understand the relationship between policy specifications and the resulting GHG emissions savings over the course of the analysis period (2020–50), several different scenarios are considered. Each scenario consists of specifications for tune-ups, EUI targets, GHG targets, and electrification. The multiple scenarios are organized into four major groups; each explores the impact of a different aspect of policy design:

- *different amounts* of required GHG emissions reduction
- *different timing* for GHG targets and electrification
- *different floor area ranges* subject to GHG targets and electrification
- *different building types* exempted from GHG targets and electrification

All four scenario groups include the base case scenario, which reflects the current situation in Seattle, and the nominal scenario, which represents Seattle's currently planned policy. All other scenarios are variations on the details of the GHG targets and electrification, which represents potential variations on Seattle's currently planned policy.

3.1 BASE CASE SCENARIO

The base case scenario reflects the current situation: buildings undergo tune-ups and are subject to the WA EPS EUI targets, but are not subject to any GHG emissions targets, nor do any buildings electrify.

Tune-ups are modeled as follows. Buildings >50k ft^2 reduce energy use by 10% in 2021. This models the tune-ups program that took place after the benchmarking data were measured (in 2018), but before the simulations begin (in 2020), and assures those savings persist over time. The 10% magnitude is an estimate from an internal analysis by the City of Seattle based on approximately 450 buildings that implemented tune-ups. This study did not relate energy savings to building types, sizes, or technologies, thus we were unable to assign tune-ups reductions with more specificity (*e.g.* different savings amounts for different buildings or fuels).

EUI targets are modeled to reflect the current WA EPS legislation: commercial buildings >50k ft^2 go through five cycles to reduce their EUI to the average EUI (for the buildings with the same building type and in the same floor area range) in a specified year. In all five cycles, buildings take two years to reduce energy use to hit the target. Also in all five cycles, buildings >220k ft^2 start reducing in the first year of the cycle, buildings of 90k–220k ft^2 start in the second year, and buildings of 50k–90k ft^2 start in the third year. The first cycle starts in 2025 and buildings must reduce to the 2020 average EUI. The last four cycles are regularly spaced by five years: buildings start reducing in 2030 to meet the 2029 average, buildings start reducing in 2035 to meet the 2034 average, buildings start reducing in 2040 to meet the 2039 average, and buildings start reducing in 2045 to meet the 2044 average.

3.2 NOMINAL SCENARIO

The nominal scenario represents policy that Seattle is currently exploring: in addition to the same tune-ups and EUI targets as in the base case, buildings are subject to GHG targets and buildings electrify.

GHG targets are modeled according to the policy Seattle is considering: all buildings >50k ft^2 would be required to reduce GHG emissions by 20% in two years, with a 2025 starting year for >220k ft^2 commercial buildings, a 2026 starting year for 90k–220k ft^2 commercial buildings, and a 2027 starting year for 50k–90k ft^2 commercial buildings. The nominal scenario specifies starting years of 2030, 2031, and 2032 for multifamily buildings with >220k, 90k–220k, and 50k–90k ft^2, respectively.

Electrification is modeled not to reflect planned legislation, but as an action that building owners may take as a means to achieve EUI or GHG targets, or as a way to reduce costs or replace end-of-life non-electric equipment with electric equipment. To model electrification, it is assumed all buildings >50k ft^2 replace 100% of their non-electric energy use with electric energy use, using

SCENARIO GROUP	SCENARIO LABEL	SCENARIO DESCRIPTION
All	Base case	Tune-ups and EUI targets only
	Nominal	Same as the base case, but with additional GHG targets and electrification
Amount	30% from 2020	Same as the nominal, except emissions are reduced 30% from the 2020 average instead of 20%
	Modeled target	Same as the nominal, except emissions are reduced to modeled values of emissions intensity
Timing	5-year delay	Same as the nominal, except GHG targets and electrification are delayed for five years
	5-year electrification	Same as the nominal, except with electrification taking five years instead of two, but ending at the same time
Floor area	>20k ft^2	Same as the nominal, except all buildings >20k ft^2 are included instead of just >50k ft^2
	All areas	Same as the nominal, except all buildings included instead of just >50k ft^2
Building type	Hospitals exempt	Same as the nominal, except hospitals are exempt from GHG targets and electrification
	Hotels exempt	Same as the nominal, except hotels are exempt from GHG targets and electrification
	Restaurants exempt	Same as the nominal, except restaurants are exempt from GHG targets and electrification
	Hospitals, hotels, and restaurants exempt	Same as the nominal, except hospitals, hotels, and restaurants are exempt from GHG targets and electrification

Table 1 Summary of scenarios.
Note: EUI = energy-use intensity; GHG = greenhouse gas.

a coefficient of performance of 2. For both commercial and multifamily buildings, electrification happens over the course of two years (*i.e.* buildings electrify fully either in the first year or in the second year). For commercial buildings, electrification starts in 2035, 2036, and 2037 for buildings >220k, 90k–220k, and 50k–90k ft^2, respectively. For multifamily buildings, electrification starts in 2040, 2041, and 2042 for buildings >220k, 90k–220k, and 50k–90k ft^2, respectively.

3.3 FIRST SCENARIO GROUP: AMOUNT OF REDUCTION

In the first scenario group, additional scenarios vary the amount of the emissions reductions. One additional scenario specifies GHG emissions must be reduced by 30% instead of by 20%. Another additional scenario specifies GHG emissions must be reduced to a fixed emissions intensity target (which is independent of emissions in previous years). These fixed emissions intensity targets are different for each building type, and based on the results of a prior modeling analysis completed by Seattle (Steven Winter Associates 2020). A full description of the methodology used to select these targets is outside the scope of this work, but in short, the targets were designed to reduce energy use by approximately 30% by 2030. Both additional scenarios model electrification in the same manner as the nominal scenario.

3.4 SECOND SCENARIO GROUP: TIMING

In the second scenario group, additional scenarios vary the timing of GHG targets and electrification. In one additional scenario, GHG targets and electrification are simply delayed by five years, relative to the nominal scenario. In another additional scenario, GHG targets are the same as in the nominal scenario, but electrification happens over the course of five years instead of two (*i.e.* buildings start electrifying three years earlier than in the nominal scenario and finish at the same time).

3.5 THIRD SCENARIO GROUP: FLOOR AREA

In the third scenario group, additional scenarios vary the floor area ranges of the buildings that are subject to GHG targets and electrification. In the nominal scenario, only buildings >50k ft^2 are subject. In one additional scenario, buildings of 20k–50k ft^2 are also subject (they start one year after the 50k–90k ft^2 buildings). In another additional scenario, buildings of all floor areas are subject (20k–50k ft^2 buildings start one year after the 50k–90k ft^2 buildings, and <20k ft^2 buildings start one year after that).

3.6 FOURTH SCENARIO GROUP: BUILDING TYPE EXEMPTIONS

In the fourth scenario group, additional scenarios vary the building types that are exempt from GHG targets and electrification. In the nominal scenario, all building types are subject. Four additional scenarios each exempted the following: (1) hospitals, (2) hotels, (3) restaurants, and (4) hospitals, hotels, and restaurants.

Table 1 summarizes the scenarios. Each group contains the base case scenario and the nominal scenario, as well as additional scenarios that are variations upon the nominal scenario.

4. DATA

Ideally, the design of a city's energy policies would be informed both by data on high-level building characteristics (*e.g.* floor area, building type, annual energy use), but also by detailed data about building assets and more time-resolved energy data. Before mandatory benchmarking ordinances, there were generally no comprehensive datasets that provided building type, floor area, and energy-use data at the city level. More recently, in many cities, a benchmarking ordinance provides high-level data for larger buildings, but neither detailed asset data nor energy data for small buildings is available.

A first step was made by combining benchmarking data and tax assessor data into one dataset that includes buildings of all types and sizes. (See the data availability section below for access to the scripts used to process the datasets.) Seattle's 2018 benchmarking dataset (Office of Sustainability & Environment n.d. b) is publicly available and includes floor area, building type, and annual energy use from electricity, natural gas, and steam. Tax assessor data used were a slightly pre-processed version of the original publicly available King County tax assessor data (King County n.d.). The tax assessor data contain only floor area and building type (*i.e.* they do not contain energy data).

Since the benchmarking ordinance cutoff for floor area is 20k ft^2, buildings below the cutoff were removed from the benchmarking data and we removed buildings above the cutoff from the tax assessor data. Thus, we avoid duplicated buildings from the two datasets; large buildings come from the benchmarking data and small buildings from the tax assessor data. Buildings with abnormally low floor area (<.500 ft^2, *i.e.* 46 m^2) were also removed from the tax assessor data.

Since the benchmarking and tax data do not use the same building types, the building types in the two datasets were mapped using a common list of 22 building types (*Figure 1*). Many records (87% of the tax assessor data) with use types were removed that either did not correspond to buildings (*e.g.* campgrounds, easements, open space) or were building types that were not applicable to this analysis (*e.g.* single-family houses, parking structures). In reality many buildings have multiple use types (*e.g.* multifamily housing on upper floors and commercial space on the ground floor), but for this analysis, it was assumed each building was a single predominant type. This means that when mention is made to, for example restaurants, the buildings are predominantly restaurants and not to the restaurant portions of buildings that have another predominant use, for example, multifamily. Other studies (*e.g.* Evans *et al.* 2019) have shown how to use detailed activity type data in stock modeling if such data are available.

Buildings with missing data (<1% of buildings) were removed from the dataset. In addition, buildings with abnormally low (<1 kBtu/ft^2, *i.e.* 37 kWh/m^2) or abnormally high (>1000 kBtu/ft^2,
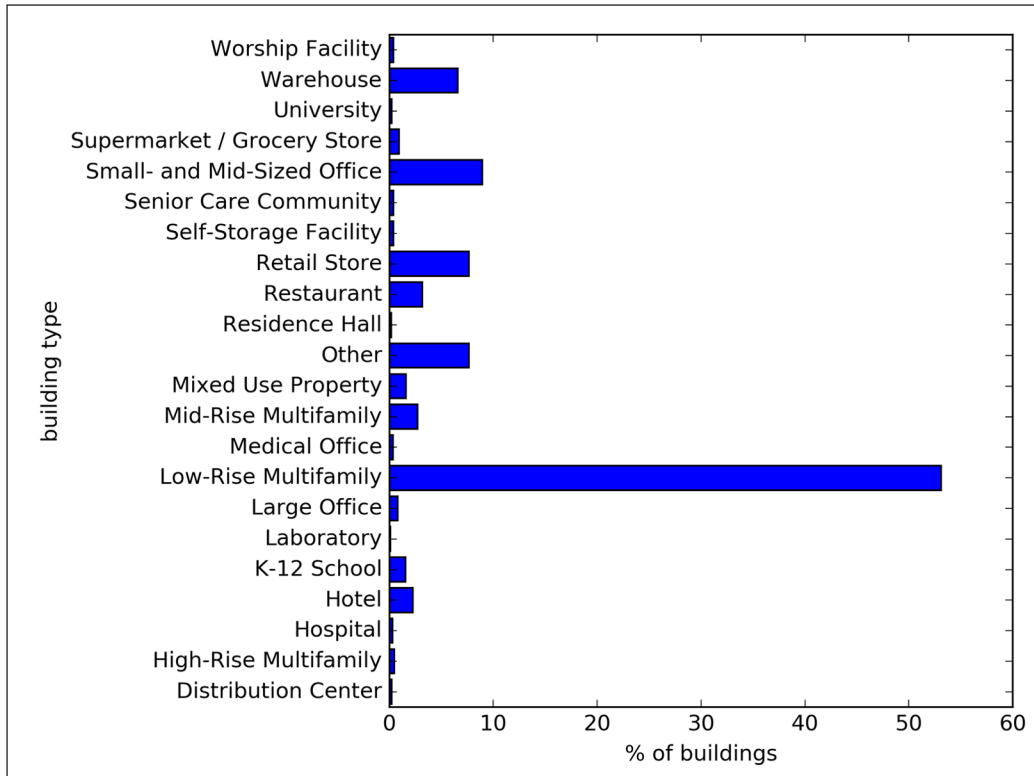
Figure 1: Percentage of buildings of each building type.

i.e. 37 MWh/m^2) values for site EUI were also removed (roughly 1% of buildings). These data were likely either entered incorrectly or were entered correctly, but the buildings are not representative of the city's building stock.

Lastly, since the tax assessor data do not contain energy-use data (only building type and floor area), we filled in energy use for the tax assessor buildings using the benchmarking data. It was reasonably assumed the tax assessor buildings use electricity and natural gas, but not steam, since all the tax assessor buildings are <20k ft^2. For each building type, two separate distributions were generated from the benchmarking data: one of site EUI and one of the proportion of site energy that is electricity (see the data availability section below for histograms of these distributions). For histogram bins with zero counts, we linearly interpolate the count from the adjacent bins. A random sample was then taken from each of those distributions (by randomly selecting a histogram bin according to its count, then sampling the value uniformly from within the bin). The samples were used to populate the tax assessor data. Using the sampled values, electricity and gas energy use was calculated by each building in the tax assessor data.

Once the two datasets had the same fields (floor area, building type, electricity use, gas use, and steam use), and since the floor area ranges in the two datasets were disjoint, the benchmarking and tax assessor data were concatenated into one combined dataset that is used for the analysis.

The combined dataset includes roughly 23k commercial and multifamily buildings with 22 different building types and floor areas from 500 ft^2 (46 m^2) to >1 million ft^2 (93k m^2). **Figure 1** shows that the large majority of buildings are low-rise multifamily, but that offices, retail, and warehouses make up significant proportions. Similarly, **Figure 2** shows that over 80% of buildings have a floor area <20k ft^2, with fewer buildings in each larger floor area range.

Figure 3 shows the percentage of emissions due to each building type. Note the drastically different shape compared with **Figure 1**. For example, hospitals make up roughly 1% of the buildings, but cause 7% of emissions. Similarly, over half the buildings are low-rise multifamily, but they only cause 13% of emissions.
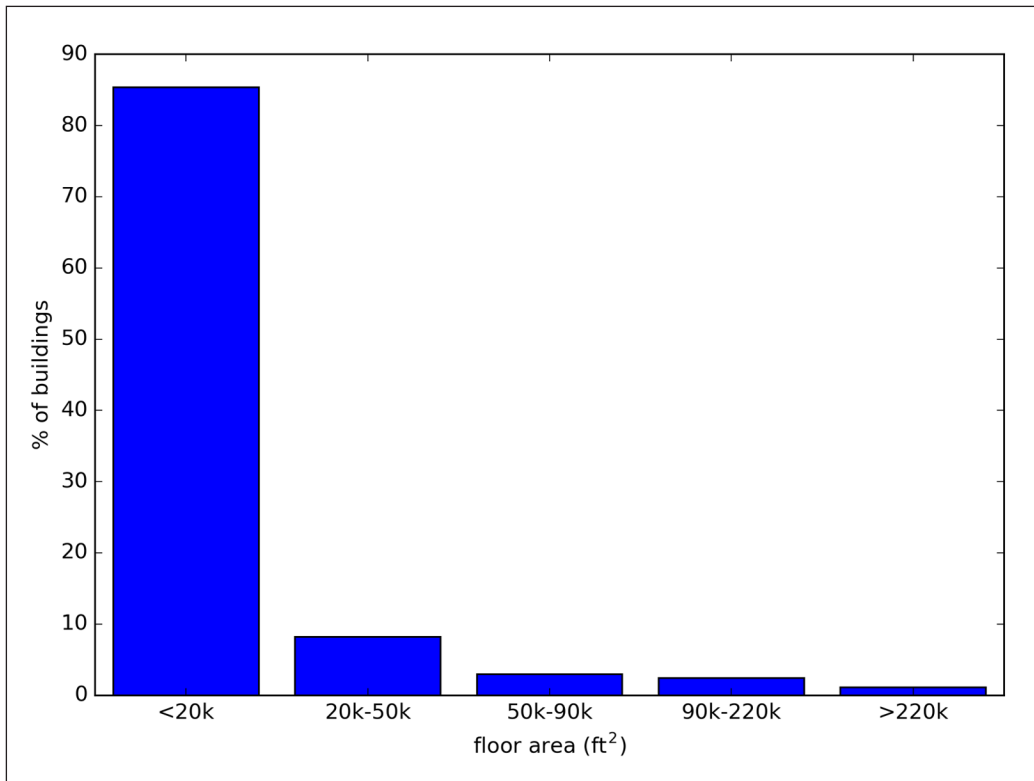
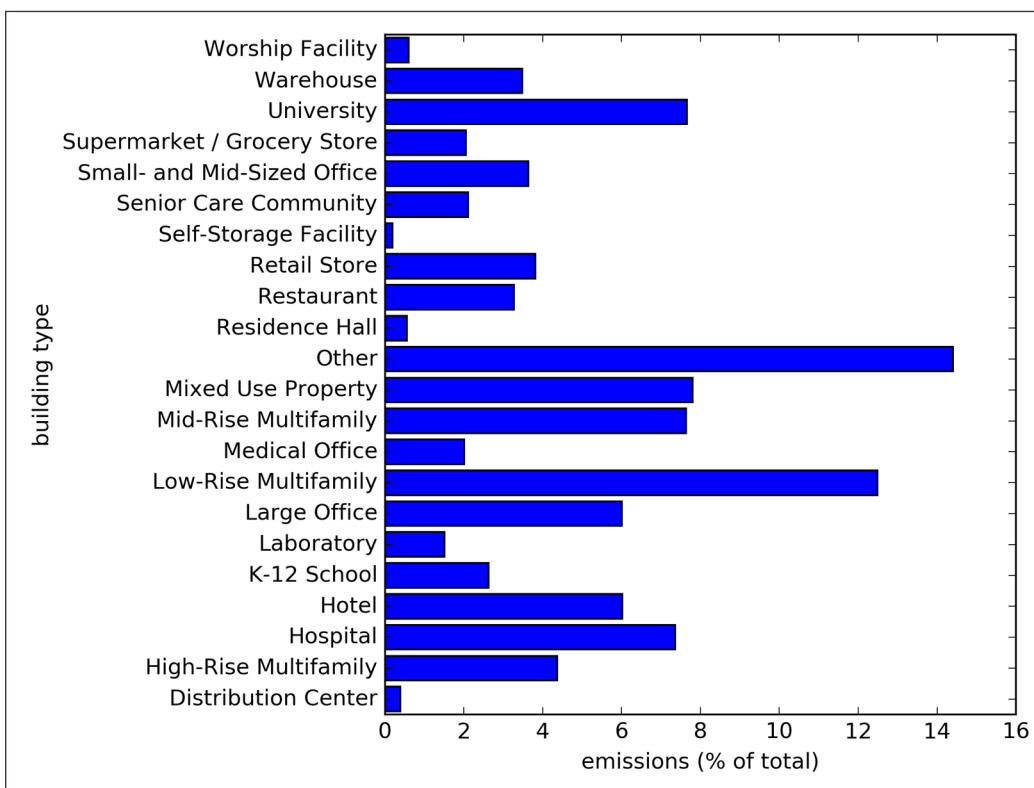**Figure 2:** Percentage of buildings in each floor area range.

Figure 3: Percentage of emissions due to buildings of each building type.

Figure 4 shows the percentage of emissions due to each floor area range. Again, its shape is quite different than that of *Figure 2*. Buildings with floor area >220k ft^2 make up only a few percent of the buildings in the dataset, but cause over one-third of emissions.

Figures 1–4 illustrate the value of an analysis approach that models each building independently by taking their size, type, and emissions into account. For example, a city might obtain large emissions reductions by targeting only a small proportion of buildings.
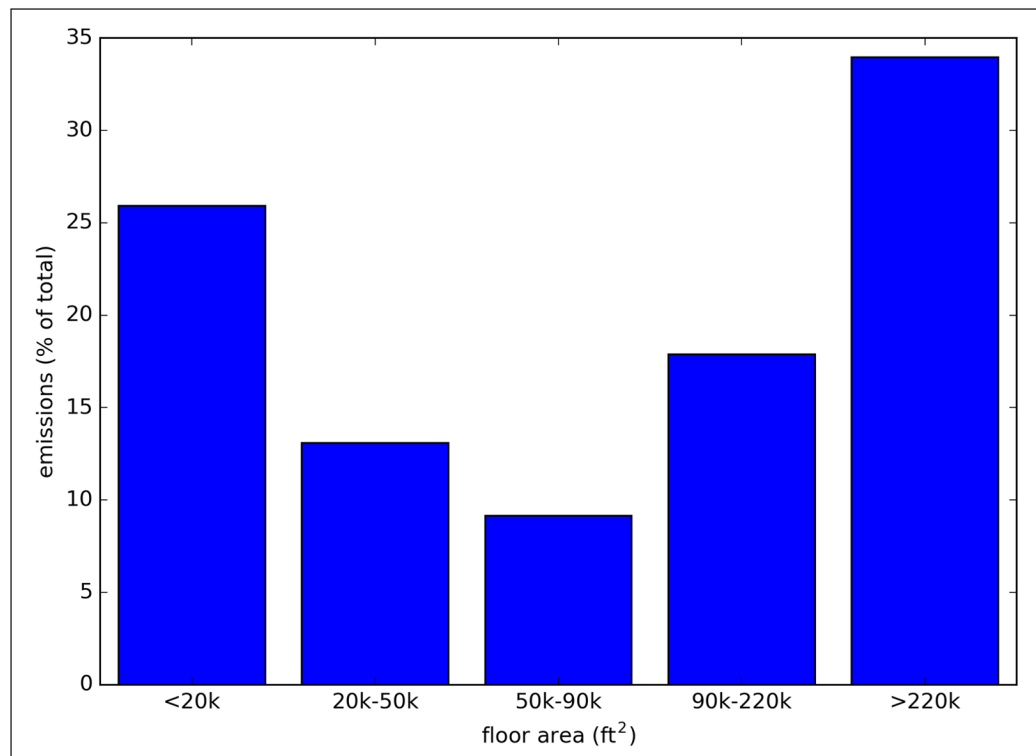
Figure 4: Percentage of emissions due to buildings in each floor area range.

5. METHODS

This section describes the model used to estimate emissions savings during each year due to each policy type. The limitations of the modeling approach and uncertainties in the methodology are then considered.

5.1 MODEL DESCRIPTION

For each building in the combined dataset, it was calculated how much energy that building would use in each year from 2020 to 2050. Electricity, gas, and steam energy use were calculated separately, and separate predictions were maintained for each cause of energy reduction (tune-ups, EUI targets, GHG targets, and electrification). Therefore, in total, for each building, and for each year, 12 different energy quantities were created (one for each combination of the three fuels and the four causes).

The starting point was the combined dataset in 2020. For each year until 2050, each building's energy use was calculated for the next year by applying energy reductions to the current year's energy use. Energy reductions were computed such that the building would reach all targets it is subject to by the target years.

In general, energy reductions are achieved over the course of multiple years. A building has a target year by which it must reduce its energy use to a target amount, and the building reduces its energy use by an equal proportion each year until the target year (*e.g.* if a 10% electricity reduction corresponds to 30 MWh and the target is three years away, the building will reduce electricity use by 10 MWh in each of the three years). However, if the building becomes subject to an additional target during that time, then the building recomputes its annual energy reduction amount so that it will achieve both the previous and new targets.

The way the energy reductions are computed depends on the cause of the reduction:

- For tune-ups, the energy reduction is specified as a proportion by which the building's energy use must be reduced, and the reduction happens in one year. A building reduces each fuel's use by the same proportion (*i.e.* for a 10% energy reduction, the building reduces electricity use by 10%, gas use by 10%, and steam use by 10%).

- For EUI targets, a building has until a target year to reduce its EUI to the average EUI of the building's peers in a particular year. A building's peers are defined as all buildings with the same building type and with floor area in the same range (50k–90k, 90k–220k ft^2, *etc.*). As with tune-ups, energy reductions for EUI targets are applied proportionally to each fuel.

- For a GHG target, the reduction amount is specified differently, depending on the particular scenario. In some scenarios, GHG emissions must be reduced to the average GHG emissions of the building's peers (again, defined by building type and floor area range) in a particular year. In one scenario, GHG emissions must be reduced to a modeled emissions intensity specific to each building type. In each case, the specified reduction is translated to a target GHG emissions value and a corresponding target year. As with tune-ups and EUI targets, energy reductions for GHG targets are applied proportionally to each fuel (based on site energy, not emissions).

- For electrification, the proportion of a building's non-electric energy use that must be replaced with electric energy use is specified, according to a specified coefficient of performance. In addition, the proportion of buildings that actually electrify is specified. With tune-ups, EUI targets, and GHG targets, all buildings reduce energy by some amount every year until the target. On the contrary, with electrification, a building replaces its non-electric energy use with electric energy use during the course of a single year, and we randomly select an equal proportion of complying buildings that will electrify in each year.

Separate portions of the energy reduction for each fuel were attributed to each of the four causes according to the following hierarchy: first tune-ups, then EUI targets, then GHG targets, and finally electrification. In other words, the assumption is that a building would first reduce its energy use to meet its tune-ups target, then, if necessary, would continue to reduce its energy use until it met its EUI target, then for its GHG target, and then for electrification. For example, in a given year, assume a building needs to reduce its energy use by 5 units to meet its tune-ups target, by 12 units to meet its EUI target, by 10 units to meet its GHG target, and by 20 units for electrification. In this case, 5 units of reduction would be attributed to tune-ups, 7 units would be attributed to EUI, 0 units would be attributed to GHG, and 8 units would be attributed to electrification.

Finally, for each year and each building, the energy reduction of each fuel due to each cause was used to compute the GHG emissions reduction due to each cause. This was based on emissions factors specific to Seattle (0.021 kgCO$_2$e/kWh for electricity, 0.18 for gas, and 0.18 for steam).

5.2 LIMITATIONS

Although the model can be a useful tool for policy planning, some assumptions were made that deserve further discussion:

- Energy-use data for buildings <20k ft^2 were generated by sampling from distributions learned from buildings >20k ft^2. No energy data were available for small buildings, and in past work, we have not seen a strong correlation between EUI and floor area.
- While the benchmarking data were actually from 2018, it was assumed that these data corresponded to 2020. More recent data were not available. We suspect that using data from two years prior would not affect the results significantly.
- New construction is not included in the model (*i.e.* the numbers of buildings of each type and size would not change over time). Reliable predictions of building stock growth were not available. It is also likely that new buildings will be energy efficient (due to new regulations) and that they will not need to reduce emissions to satisfy the proposed policies.
- A fixed 10% energy reduction was assumed due to tune-ups for all buildings, regardless of type or size. This energy reduction estimate is the result of a preliminary analysis on the overall impact of the program based on measured savings from an initial cohort of buildings. Estimates for particular building types and sizes were not available, neither was the underlying tune-ups dataset. In addition, the emissions due to tune-ups are relatively minor when compared with the EUI targets, GHG targets, and electrification (*Figure 5*).
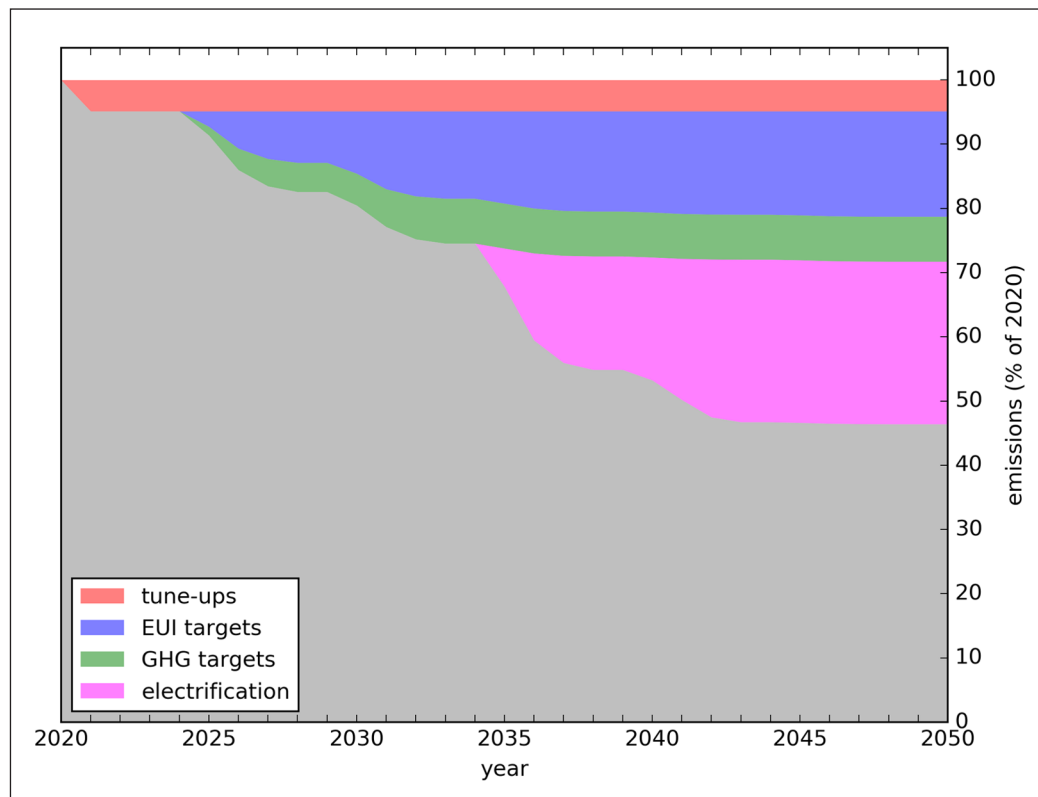
Note: The grey wedge indicates
the total emissions in each year
for all buildings. The colored
wedges indicate avoided
emissions attributed to the
different causes.

- The model does not consider which specific measures would actually be taken to achieve
  energy reductions. It was therefore assumed that energy reductions are proportional for
  each fuel. No asset data for these particular buildings were available, nor were energy data
  specific to particular end uses, so we were unable to predict whether reductions would be
  achieved by operations improvements, equipment replacement, *etc.*
- The same emissions factors (provided by Seattle) were used for the period 2020–50. We
  think it is unlikely they will change significantly over that period.
- The model does not include the cost of implementing the emissions reductions. Although
  costs are a key consideration in policy planning, there were no reliable cost data specific
  enough to be applicable to this analysis. In future we plan to expand this study to
  incorporate costs.

Although many of these limitations will affect the accuracy of the emissions predictions for
individual buildings, in aggregate the effects on city-wide emissions (which are the focus of this
study) are minimal.

Regarding uncertainty in predictions due to our data sources and methodology:

- Primarily, uncertainty is addressed by modeling different possible policy specifications
  and the resulting actions taken by buildings to comply. For a given scenario, our results
  are deterministic, but by presenting the results for many scenarios, a range of potential
  outcomes is demonstrated.
- The inputs to the model (*i.e.* floor area, building type, and energy use for each building)
  are from benchmarking data (for large buildings) and a combination of tax assessor data
  and sampling from assumed distributions (for small buildings). Benchmarking ordinance
  compliance is very high and tax assessor coverage is largely accurate. Benchmarking energy
  data are considered to be reliable. While some uncertainty stems from using sampled
  energy data for small buildings, this uncertainty is significant for individual buildings, but
  mitigated for aggregated city-wide results.
- Beyond the previous two items, the modeling assumptions listed above contribute additional
  uncertainty to the predictions. Due to insufficient data, we were unable to quantify this
  uncertainty in a meaningful way.

Furthermore, the large majority of the sources of uncertainty have the same effect on all scenarios. While the results for a particular scenario are of interest, a key aspect of this paper is the comparison of one scenario (*i.e.* one policy implementation) with another. Since both the compared scenarios are subject to the same uncertainty, the uncertainty has minimal impact on the relative comparison.

6. RESULTS AND DISCUSSION

Figure 5 illustrates the GHG emissions (as a percentage of 2020 emissions) from all buildings (the grey wedge) over the analysis period (2020–50) for the nominal scenario, as well as the avoided emissions due to the different causes (the color wedges). Note that the analysis does not include growth in emissions due to constructions of new buildings, but instead assumes the building stock remains as in 2020. Tune-ups cause a one-time reduction in 2021 of roughly 5%. Starting in 2025, the EUI and GHG targets begin reducing emissions, with the magnitude of the reductions increasing over time (due to additional building sizes and types phasing in, and the additional EUI reduction cycles beginning each five years). By 2050, EUI targets have reduced emissions by an additional 16%. By 2035, GHG targets have finished (note that the green band no longer widens) and has caused another 8% reduction. Buildings begin electrifying in 2035, emissions reductions increase each year as additional buildings electrify, and by 2050, electrification has reduced emissions by another 25%. Overall, the proposed GHG targets contribute modest savings beyond the current EUI targets, but that electrification has the most dramatic effect.

In the nominal scenario, emissions in 2050 are 0.262 million $MtCO_2e$, and cumulative emissions from 2020 to 2050 are 11.9 million $MtCO_2e$. For comparison, if emissions continue as in 2020 (*i.e.* if there were no tune-ups, EUI or GHG targets, or electrification), cumulative emissions from 2020 to 2050 would be 17.6 million $MtCO_2e$. In the base case scenario (*i.e.* only the current Seattle tune-ups and WA EPS EUI policies are in place), cumulative emissions would be 14.6 million $MtCO_2e$. Thus, implementing the nominal scenario (*i.e.* the GHG emissions and electrification policies in addition to the current tune-ups and EUI policies) would save 2.72 million $MtCO_2e$ more than the base case scenario.

Also in *Figure 5*, note that the slope of a given curve changes each year, sometimes dramatically. This is due to a target starting or stopping, additional buildings being phased in, and the fact that those additional buildings might have combined emissions that are significantly different than those of the buildings phased in during the prior year. For example, when electrification begins, the >220k ft^2 buildings electrify first, followed by the 90k–220k ft^2 buildings. The slope of the emissions curve is steeper when the larger buildings are electrifying because that size group emits more (*Figure 4*). In general, during each phasing cycle, the slope tends to decrease because larger buildings are phased in first and they emit more. For buildings <50k ft^2, larger buildings actually emit less (*Figure 4*), but in the nominal scenario shown in *Figure 5*, none of the policies applies to buildings <50k ft^2. Also note that the savings due to EUI targets tend to flatten out over time. In each of the five cycles, buildings with above-average EUI must reduce to the average. With each additional cycle, fewer buildings have an EUI significantly above average, so the reduction needed to reach the average is less during each cycle.

Though not explicitly shown here, we experimented with the effects of implementing multiple reduction causes individually as compared with simultaneously. An example is provided with EUI targets and GHG targets as the causes, but these results hold for other causes as well. When both EUI and GHG targets are in place, the savings were found to be greater than the sum of the savings with each target type separately. This is because there can be some buildings that save more by meeting the EUI target than the GHG target, and other buildings that save more by meeting the GHG target. With both targets in place, each building must meet the target causing more savings for that particular building.

Figure 6 shows cumulative GHG emissions savings (*i.e.* total emissions saved in all years from 2020 to the year on the horizontal axis) for the emissions-reduction-amount scenario group. In the
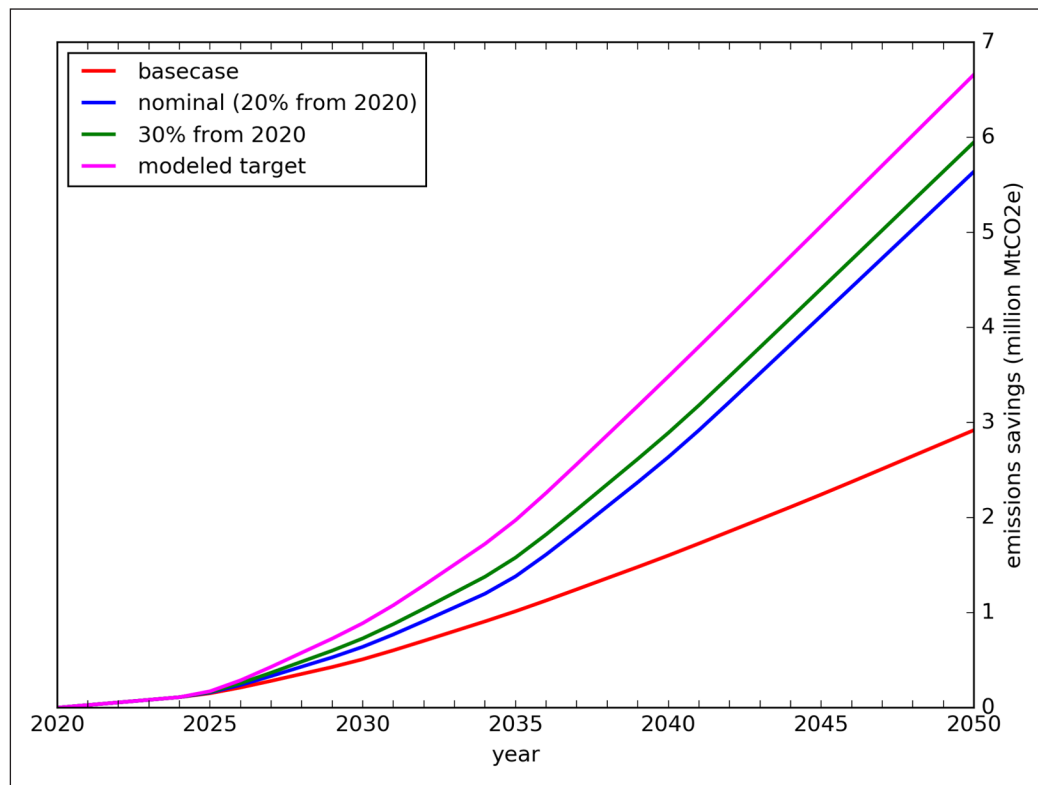
base case, buildings are not subject to GHG targets or electrification. In the nominal scenario, GHG emissions must be reduced by 20% from the average in 2020, and buildings must electrify. In one additional scenario, emissions must be reduced by 30% from the 2020 average. In the second additional scenario, emissions must be reduced to a modeled emissions intensity target. In the two additional scenarios, buildings electrify in the same way as in the nominal scenario. As expected, the nominal scenario causes significantly more savings than the base case (including significant savings due to electrification) (*Figure 5*). Requiring a 30% reduction causes a modest difference in savings relative to the 20% policy, and the modeled emissions intensity targets cause significant savings relative to the 20% policy.

Figure 7 shows cumulative emissions savings for the timing scenario group. The base case scenario has no GHG targets or electrification. In the nominal scenario, GHG emissions must be reduced by 20% from the 2020 average and each building has two years to electrify. In one additional scenario, GHG targets and electrification are the same as in the nominal scenario, except that they all start five years later. In the other additional scenario, GHG targets are the same as in the nominal scenario, and electrification ends at the same time, but buildings electrify over the course of five years instead of two. In both additional scenarios, once all targets and electrification have been enacted and finished, the emissions in a given year are the same as in the nominal scenario, but since the savings start sooner or later, the cumulative emissions savings are different. Compared with the nominal scenario, delaying by five years significantly reduces the cumulative emissions savings, but allowing electrification to start five years before the policy ends instead of two causes slightly more savings. In the scenario with five-year electrification, only some of the savings occur earlier: the GHG targets savings happen at the same time as in the nominal scenario, and some of the electrification savings happen at the same time (*i.e.* the buildings that electrify during the final two years of the five-year window). However, in the scenario with a five-year delay on both GHG targets and electrification, all the savings are delayed, and thus the impact on cumulative savings is larger than when only some of the savings are delayed. In short, the sooner the savings occur, the greater the cumulative savings. We should note that from a climate change perspective, cumulative emissions savings over a long time horizon are a more relevant metric than emissions in the final year of that same time horizon.
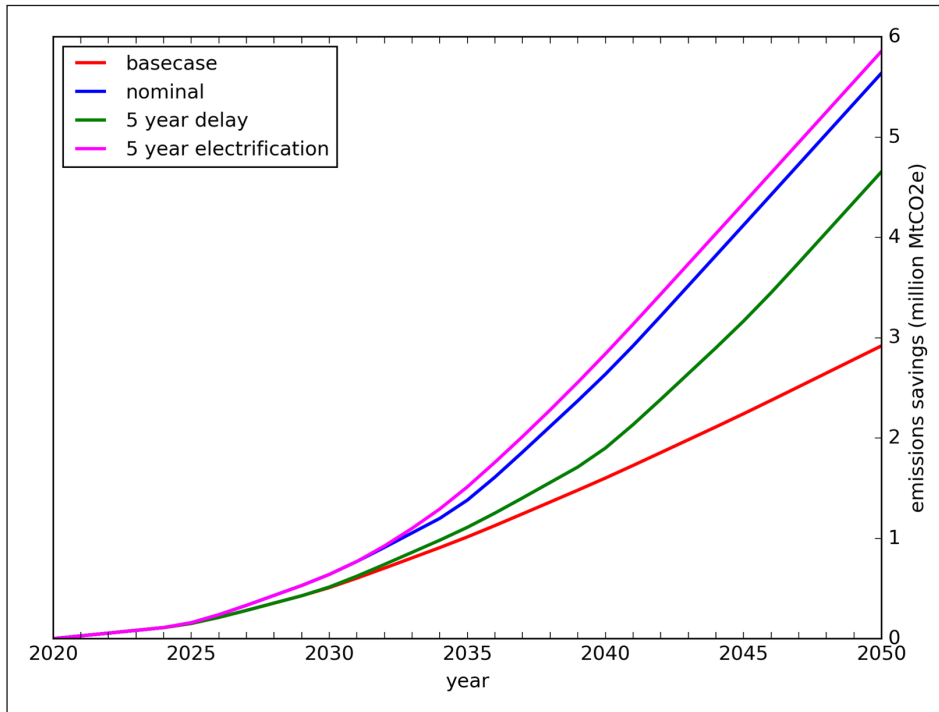
Figure 8 shows cumulative emissions savings for the floor area scenario group. The base case scenario has no GHG targets or electrification. In the nominal scenario, all buildings >50k ft^2 are subject to GHG targets and electrification. In one additional scenario, buildings 20k–50k ft^2 are also subject. In another additional scenario, buildings of all floor areas are subject. Intuitively, in both additional scenarios, subjecting more buildings increases the emissions savings, relative to the nominal scenario. The additional savings due to including the 20k–50k ft^2 buildings are significant, but not as large as the additional savings due to including the <20k ft^2 buildings. This is consistent with *Figure 4*, in which the total emissions from the <20k ft^2 range are larger than those from the 20k–50k ft^2 range. However, since there are far more buildings in the <20k ft^2 floor area range than in the 20k–50k ft^2 range (*Figure 2*), the cost of implementing the policies for the <20k ft^2 buildings should be weighed against the additional emissions savings.
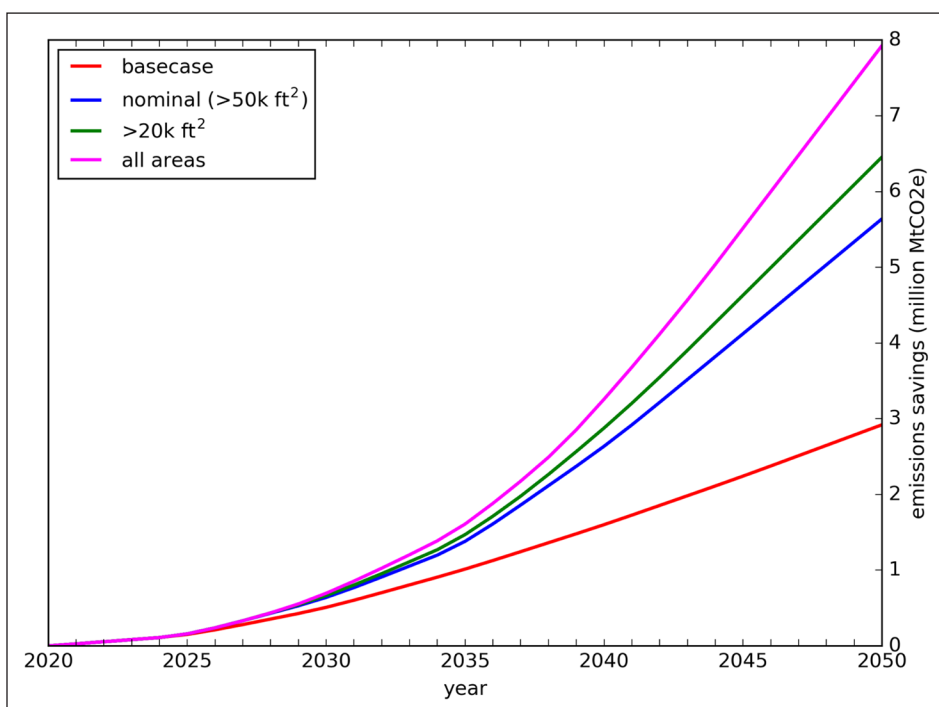

Figure 8: Cumulative emissions over time for scenarios with varying floor area ranges subject to greenhouse gas (GHG) targets and electrification.

Figure 9 shows cumulative emissions for the building type scenario group. The base case scenario has no GHG targets or electrification. In the nominal scenario, all buildings >50k ft^2 are subject to GHG targets and electrification. Seattle was interested in exploring the effect of exempting selected building types either because they are too complex or because of other stakeholder considerations. In one additional scenario, hospitals are exempt from both GHG targets and electrification. In another scenario, hotels are exempt, and in another, restaurants are exempt. Finally, in a fourth additional scenario, all three building types (hospitals, hotels, and restaurants) are exempt. Intuitively, exempting buildings from the policies reduces emissions savings, and the magnitude of the reduction depends on the building type (or types) being exempted. *Figure 3* shows that restaurants (*i.e.* buildings that are predominantly restaurants) cause roughly 3.5% of total emissions, while hotels and hospitals cause around 6.0% and 7.5%, respectively. However, in *Figure 9*, exempting restaurants has virtually no impact on savings, while exempting hotels and hospitals has a significant impact. This is because the scenarios shown in *Figure 9* only apply to buildings >50k ft^2, and very few restaurants in Seattle are >50k ft^2.
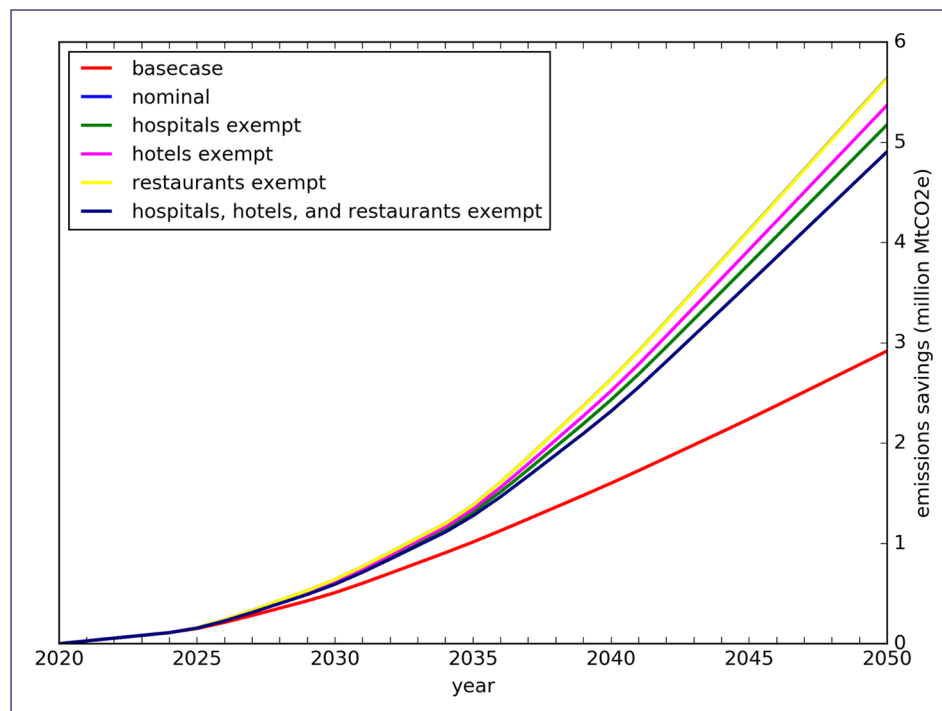

Figure 9: Cumulative emissions over time for scenarios with varying building types exemptions.

Note: The yellow curve is almost exactly on top of the medium blue curve.

SCENARIO GROUP	SCENARIO LABEL	CO$_2$E SAVINGS
All	Nominal	19%
Amount	30% from 2020	21%
	Modeled target	26%
Timing	5-year delay	12%
	5-year electrification	20%
Floor area	>20k ft^2	24%
	All areas	34%
Building type	Hospitals exempt	15%
	Hotels exempt	17%
	Restaurants exempt	19%
	Hospitals, hotels, and restaurants exempt	14%

Table 2 Cumulative emissions savings relative to the base case for each scenario.

Note: See *Table 1* for scenario descriptions.

In summary, cumulative emissions from 2020 to 2050 would be 17.6 million $MtCO_2e$ if no legislation were implemented, and would be 14.6 million $MtCO_2e$ with only the currently implemented tune-ups and EUI targets (*i.e.* the base case). In the nominal scenario, GHG targets and electrification would also happen, causing cumulative emissions to be 11.9 million $MtCO_2e$ (a savings of 19%, relative to the base case). We explored several variations of the nominal scenario. ***Table 2*** shows each variation with its 2020–50 cumulative emissions savings, relative to the base case. Adjusting the amounts of reductions required can yield an additional 7% savings beyond the nominal scenario; adjusting the timing can either lose 7% or gain 8%; adjusting the floor area range can gain 15%; and exempting building types can lose 5%.

7. CONCLUSIONS

Cities throughout the US are considering policies that will address climate change by requiring buildings to reduce their greenhouse gas (GHG) emissions, but challenges remain. Data availability limits the fidelity to which models can be built, and the details of policy implementation can significantly impact the results in unpredictable ways.

A new methodology was presented that uses relatively common datasets (benchmarking and tax assessor data) to construct a model of a city's building stock. The model was then used to predict the resulting emissions savings due to implementing GHG targets and electrification. Several different variations were explored on the nominal policy (amount of required reductions, timing of reductions, and building sizes and types that reduce) to quantify the impacts of different policy implementations.

The model shows that additional GHG targets and electrification could reduce cumulative emissions from 2020 to 2050 by 19% from their nominal state, but by varying the details of these policies, savings could be between 12% (by delaying five years) and 34% (by including all building sizes). In short, the details of the policies can have a very large impact on emissions (and thus on climate change). It is recommended that the policies be implemented as soon as possible and not be limited to buildings >50k ft^2.

This methodology can be applied to other cities besides Seattle with relatively few changes, provided those cities have benchmarking ordinances in place that collect annual energy use, floor area, and building type, and tax assessor data that contains floor area and building type for all buildings not covered by the benchmarking ordinance. However, different cities will have different results. For example, a study conducted for Washington, DC (C40 Cities & LBNL 2019), showed that including smaller buildings in performance-based policies did not result in significantly more savings (probably due to a different distribution of small and large buildings in Washington, DC, than in Seattle). Another important distinction is that nearly all of Seattle's electricity is generated by hydroelectric dams, thus making the emissions factor for electricity much lower than for many parts of the country.

The study was limited to whole building energy use and did not include consideration of end-use savings, the impacts of specific technologies and strategies, or their embodied carbon. Such analysis would require additional data on building system characteristics and end use-specific energy data, which were not available. In future work, such data combined with whole building benchmarking data could provide additional insights into technology pathways to achieve net zero emissions goals (*e.g.* de Oliveira Veloso *et al.* 2020). Our analysis showed (see the supplemental figures in the data availability section) that city-wide energy savings of approximately 35% by 2050 would be required to achieve the emissions reductions required by the nominal scenario, an amount that is well within the range achievable with currently available technologies.

Several possible improvements to the methodology are feasible, based on data availability. If more building characteristics (*e.g.* year built) were included in the datasets, it would be possible to explore the impacts of policies that targeted buildings by age. If asset data were available, a policy might target buildings based on their assets (*e.g.* buildings with a boiler more than 10 years old must either replace the boiler or electrify). If energy consumption data were split by end use, a

policy could target buildings with, for example chiller load that is too large a proportion of the total load. If sub-metered energy data were available, it would be possible to target different portions of the building differently (*e.g.* a restaurant on the bottom floor of a multifamily building might be exempt while the rest of the building is not).

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AUTHOR AFFILIATIONS

Travis Walter ⓘ *orcid.org/0000-0002-3949-8470*
Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, Berkeley, CA, US
Paul Mathew ⓘ *orcid.org/0000-0002-4505-6396*
Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, Berkeley, CA, US

AUTHOR CONTRIBUTIONS

Both authors were responsible for conceptualization, investigation, methodology, and writing. The first author was also responsible for formal analysis, software, and visualization. The second author was also responsible for funding acquisition, project administration, and supervision.

COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

The benchmarking dataset is publicly available (Office of Sustainability & Environment n.d. b). The tax assessor dataset was provided by the City of Seattle under the condition of confidentiality. The original King County tax assessor dataset is publicly available (King County n.d.). Additional figures resulting from the analysis are available to the public at *https://github.com/TravisWalterLBNL/ ghg-policy-impacts-for-seattles-buildings*. The same site provides the scripts used to process the data, run the model, and generate the figures. The model outputs are also available from the corresponding author upon reasonable request.

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