

Combining Urban Building Energy Models with Retrofit Adoption Models for Time-Dependent Carbon Emission Projections and Equity Implications

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ABSTRACT

To meet global climate goals, most of the world's existing buildings will need to be retrofitted by 2050. How do we achieve this in an equitable and scalable manner? The authors previously developed and tested urban building energy modeling (UBEM) workflows and communication processes that allow municipalities worldwide to quantify the effect of stock-level retrofits on their building-related carbon emissions. The resulting technology pathways provide a concrete set of measures to reach carbon reduction goals. However, this analysis ignores the socioeconomic realities of the inhabitants of the investigated buildings which make it extremely unlikely that some retrofits will be realized unless more deliberate financial and logistical support mechanisms are put in place. In this paper, we integrate UBEM workflows with a complementary retrofit adoption model that is based on block-level U.S. census data. Underlying adoption rates are based on a thorough literature review and consider home ownership, payback times, and retrofit costs in relationship to household income. We test our model on 13,100 residential buildings in Oshkosh, WI, and find that – even with optimistic adoption rates – projected emissions reductions by 2050 fall well below local carbon reduction goals. We further generate heat maps of retrofit adoption across Oshkosh and find deeply divided adoption patterns separated by household income and building ownership. We hope that local and state level policymakers will use the results from this study to formulate highly customized incentive structures that address the twin goals of expedited *and* equitable building stock renewal by 2050.

Introduction

Municipalities worldwide have been publicly sharing mid-century greenhouse gas emissions reduction goals to align with Paris Agreement targets to address climate change. With buildings oftentimes responsible for more than half of a municipality's current carbon emissions, they play a prominent part within most carbon reduction strategies (JLL 2022). To link political ambitions to physical realities, we previously developed a collaborative simulation workflow called UBEM.io that breaks up the generation process of an urban building energy model (UBEM) of an existing building stock into a set of discrete steps (Ang et al. 2022a): A local sustainability champion, responsible for foreseeing a municipality's carbon reduction efforts, works with the local GIS manager who maintains a digital model of the built environment. The GIS manager uploads a shapefile along with building attributes such as height, age, and use type to UBEM.io after which a sustainability consultant, hired by the city, explores various, locally appropriate building retrofit packages and applies them to the resulting UBEM of the municipality. An UBEM consists of high level, individual physics-based building energy models (BEM) of each structure in a city that can be used to model stock level energy use and carbon emissions (Reinhart and Cerezo Davila 2016). UBEM.io uses the Urban Modeling Interface (UMI), a

Rhinoceros 3D based simulation platform based on the U.S. Department of Energy’s EnergyPlus whole-building energy modeling software (Reinhart et al. 2013). UBEMs can be used for various applications targeting different end users, such as stock-level analysis for city planners and building-level recommendations for individual building owners (Ang, Berzolla, and Reinhart 2020). The results of an UBEM.io analysis consists of various scenarios of current and future carbon emissions for a given building stock. Figure 1 shows a sample output for the city of Oshkosh, WI, based on a previous study, details of which are provided in the methodology section (Berzolla 2021).

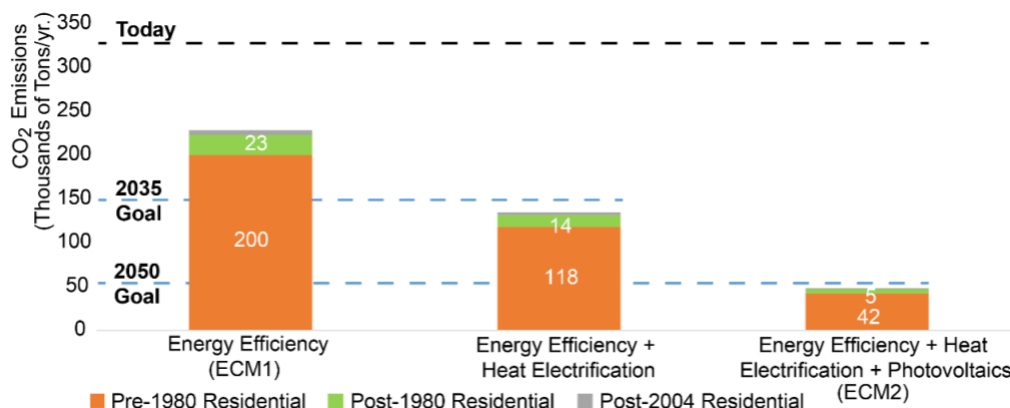


Figure 1. Technology pathways to Oshkosh's 2050 emissions reduction goal. The ECM1 package used in this study corresponds to Energy Efficiency and leads to a 31% emissions reduction. ECM2 corresponds to Energy Efficiency, Heat Electrification, and Photovoltaics (the right-most technology pathway) and leads to an 85% emissions reduction. *Source:* Berzolla 2021.

The key takeaway is that Figure 1 offers a set of so-called technology pathways, i.e. a package of building retrofits and renewable energy deployment that gets a community to its carbon emissions reduction goals for the built environment (Berzolla 2021). These powerful pathways offer concrete measures for communities around the globe to achieve their greenhouse gas (GHG) reduction targets. We have since tested the concept in over a dozen communities across the globe, confirming both the scalability of the effort as well as the relevance of the resulting information for urban policymakers (Ang et al. 2022b). However, these previous analyses ignore the socioeconomic realities of the residents of the investigated buildings as well as how fast these various technologies may be implemented. Napkin math shows that the current 1% adoption rate of building retrofits is far too low to achieve anything near the technically feasible technology pathways that would get a city to its emissions reduction goals in 30 years (IEA 2021). Furthermore, communities are diverse with differing socioeconomic and demographic statuses – such as income, education, and home ownership levels. These factors, among others, will affect the actual adoption of retrofits in the built environment, crucial to meeting the city’s emissions reduction goals. For example, the U.S.’s Weatherization Assistance Program (WAP), which is aimed at low-income homeowners, only leads to an average energy savings of 25%, far below levels needed to achieve emissions reduction goals (U.S. Department of Energy 2021).

Different technology upgrades also compete. For example, an owner who purchases a new, high efficiency gas furnace today effectively locks in this technology and the underlying infrastructure for the coming decades. To help cities better gage the speed and type of upgrades residents will consider, we introduce a framework that connects UBEM-based emissions

reduction predictions with a census block level technology adoption model. Both modeling approaches are bottom-up, based on individual buildings and thus complement each other. As we will see, they support micro-scale predictions of when and where retrofits of various types are likely to occur. This information is crucial for policymakers aiming to speed up the progress to meet looming carbon reduction deadlines while ensuring that no neighborhood is left behind. Following a review of technology adoption research, we present an initial building retrofit adoption model for buildings and apply it to the city of Oshkosh, WI.

Background

Just because a technology exists and is economically sensible, i.e. the person paying for the technology will eventually get their investment back, does not mean that it will ever be widely implemented. Economic feasibility is of course a necessary requirement for most investments which is why literature on building retrofits has thus far focused on this metric at the individual building, city, and country scale (Langevin, Harris, and Reyna 2019). For example, Wilson et al (2017) studied economically-feasible retrofits in terms of eliminating retrofit packages that did not achieve a simple payback period of less than five years, and suggested that homeowners typically consider only retrofits with a quick payback period.

To further understand technology adoption over time, another key factor has been identified: market potential (Packey 1993). Whereas economic potential depends on the cost of the upgrade and the income of the potential homeowners, market potential tries to understand what percentage of all economically feasible retrofits will ultimately be implemented and/or adopted (Packey 1993). Transferring these concepts to the building retrofit market, an adoption analysis needs to account for the actual pool of eligible residences and the relative cost of various retrofit options vis-à-vis inhabitants' household income.

Interestingly, while there is extensive literature on the diffusion of products such as Roger's "Diffusion of Innovation," there is very little documented data on adoption of building retrofits (Rogers 1976). To the best of our knowledge, the only in-depth study of building retrofit adoption was carried out for the U.S. Department of Energy by the Arthur D. Little company as part of a broader energy technology potential model in the 1970s (Glesk 1979). In this work, we predict total market potential for building retrofits such as insulation and equipment upgrades based on two key factors: upfront cost and payback period. Yet no additional modeling or analysis for the built environment along similar lenses has been done since. There is, however, expansive literature on the adoption of photovoltaics (PV) (Dong and Sigrin 2019; Mohandes, Sanfilippo, and Al Fakhri 2019). While an analogy to PV is useful, the deep building energy retrofits required to meet emissions goals are a lot more disruptive to residents' life and the economics are more uncertain, especially considering the potential rebound effect of somewhat increased energy consumption post-retrofit (Gillingham, Rapson, and Wagner 2014).

Consequently, more research must be done to better understand the potential for the adoption of building retrofits. To develop a sense for the required order of magnitude of different adoption rates, we base our initial adoption model on the oft-cited baseline building retrofit rate of 1% (IEA 2021). This figure is an upper estimate as it includes non-energy renovations of buildings and additions. While some of these renovations may be driven by thermal performance goals, many are driven by owners' desires to remodel their homes for various reasons. These renovations may or may not include more efficient construction practices. An old home that is remodeled may get new, higher-performance windows simply because that is what is available on the market today. These non-energy driven retrofits are important because the cost of certain

upgrades such as new windows may be cost prohibitive on their own. However, these energy efficiency co-benefits are likely limited and are encompassed by our 1% retrofit rate assumption. For example, in Massachusetts, while 9% of owner-occupied single family homes are renovated each year, only 5% of these include adding insulation, for a less than 0.5% adoption rate (NMR Group 2020). In the U.S. as a whole, the American Housing Survey estimates that the rate for retrofits that included insulation in 2020 was a paltry 0.07% (U.S. Census Bureau 2021a).

Another confounding factor for building upgrades is ownership: It is nearly impossible for tenants to initiate the installation of photovoltaics or other building retrofits and they are not incentivized to do so (Sigrin et al. 2016). There have been proposed approaches to overcome the landlord/tenant barrier in Europe, but barring major policy shifts that require landlords to meet energy efficiency standards in rental units and/or substantially expanded budgets to adequately incentivize landlords to take action, few if any rental units will be voluntarily retrofitted (Galvin and Sunikka-Blank 2017). Therefore, in this analysis we propose limiting the pool of eligible homes to only those that are owned to reflect current political realities in the U.S. Scenarios where home ownership is not accounted for show the potential emissions reductions if new policies or incentives are implemented to break down this ownership barrier.

Methods

For this study, we combine the state of the art in urban building energy modeling with existing adoption models to predict the adoption of technology pathways defined and tested with the UBEM. As a case study, we use an existing UBEM of Oshkosh, WI consisting of 13,100 residences. We then present three levels of refinement to the 1% retrofitting rate to illustrate how adoption occurs in the city.

Oshkosh UBEM Emissions Model

In the original Oshkosh case study, we outlined two pathways for the residential buildings in Oshkosh: Energy Conservation Measure 1 (ECM 1) and ECM 2. ECM1 is an energy efficiency retrofit using the EnergyStar Home standard as a guide, including reductions in equipment and lighting loads through energy efficient appliances and LED lighting, reduction in thermal losses through blow-in insulation and continuous external insulation, and reduced infiltration through air sealing. Finally, as per EnergyStar Home standards, a 95% efficient condensing gas furnace is installed. The ECM2 package includes everything in the energy efficient retrofit in ECM1 but additionally replaces the gas furnace with a cold-climate heat pump and installs a 10 kW PV array on the roof. The PV array size was chosen at the city-scale to provide the remaining emissions reductions beyond the reductions from the efficiency and heat electrification alone. These are two sensible and comprehensive upgrade packages that can be done with today's technology and will lead to substantial emissions reductions for most homes.

The residential building stock in Oshkosh was broken down into three major archetypes that describe the construction properties, loads, and schedules in the residential buildings: pre-1980, post-1980, and new (post-2004).¹ The pre-1980 and post-1980 residences account for 99% of the

¹ Archetypes are composite representations of buildings in a city, neighbourhood or community with relatively similar physical characteristics and properties.

buildings included in the Oshkosh study area and are the focus of this analysis, as it is assumed most new homes will not be retrofitted before 2050.

The Oshkosh UBEEM yields energy consumption data for each building and scenario by fuel type (electricity and natural gas). We then calculated the emissions based on the emissions factor for each fuel type. Figure 1 shows the carbon emission for each of the three scenarios assuming 100% adoption for ECM 1, ECM2 without PV, and ECM2.

It is worth noting that the original case study in Oshkosh used a fixed emissions intensity for grid electricity based on the local utility's 2020 reported value of 0.54 kg CO₂/kWh. While this was desired by the decisionmakers in Oshkosh, it is not reflective of the future emissions reduction potential from a decarbonizing power grid. For the adoption framework describe below, a more realistic approach to emissions from the grid was used: the National Renewable Energy Laboratory's Cambium dataset (Gagnon et al. 2021). Cambium predicts grid emissions by state under a variety of different decarbonization pathways. For this study, the Mid-case scenario for Wisconsin was used. This Mid-case corresponds to large growth in renewables but uncontrolled fossil fuel capacity at lower utilization rates with carbon capture (Cole et al. 2021). This scenario represents a high growth of renewable energy generation but without the wholesale shift away from fossil fuels that seems unlikely without drastic policy changes in the US. It is worth noting that the 2021-2025 emissions intensity is higher in the Cambium dataset than the value provided by the utility for Oshkosh. Consequently, the baseline emissions are not fully aligned with the previous technology pathways study.

Adoption Model

For the initial adoption model laid out in this paper, we assume that 1% of the building stock will be renovated each year. As explained above, this assumption is probably optimistic and does not yet consider the effect of more targeted incentive structures. For our baseline scenario, called "1% all buildings," we assume that the adoption rate for all buildings is the same. For each year in the projection, we go through all buildings in the UBEEM model and "throw the dice" as to whether the building is retrofitted, with a 1% total likelihood that each building is upgraded to either ECM1 or ECM2, or 0.5% for each upgrade. Given the 20+ year lifespan of a gas furnace, packages ECM1 and ECM2 are mutually exclusive. We accordingly assume that only one package or the other will ever be adopted per building between now and 2050. Once the building has been updated, it is ignored in future years. Given that ownership and household income affect the adoption of retrofits, we further introduce more realistic scenarios with varying adoption rates between buildings and ECMs.

Ownership

One of the major limitations in predicting adoption is that retrofits occur at the individual building level but key metrics such as ownership are only readily available from census data that is reported at the block level. Consequently, we propose a stochastic modeling approach to assign census data to individual buildings. The relevant census characteristics are assigned to buildings before each model simulation based on its likelihood from the census data. E.g., if a building falls in a block group with 25% ownership according to the census, our refined model scenario, called "1% with ownership," throws the dice for each building to determine owner occupancy before beginning the thirty-year retrofit adoption simulation. For the example building, this will stochastically happen once every four iterations. Buildings that are not owner-occupied are discarded. To maintain an overall annual retrofit adoption rate of 1%, we calculate

an adjusted adoption rate for the initial pool of owned eligible buildings. For Oshkosh, where ~63% of residences are owned across the city, the effective adoption rate for owner occupied buildings is 1.6%. We again evenly split this between ECMs, leading to 0.8% for each.

Upfront Cost and Payback Period

Building retrofits, especially the “deep” retrofits required to meet emissions reduction goals, are expensive. It is thus expected that ECM1 will have a higher adoption rate than ECM2. To attempt to quantify this split, a third model scenario, “1% with ownership and costs” uses a market penetration analysis inspired by the Arthur D. Little model (Glesk 1979). The Little model predicts the total market penetration of a building technology based on the upfront cost and the undiscounted simple payback period (Glesk 1979). The Little model is from 1979 so we normalize the first cost based on the \$16,841 median household income in 1979 (U.S. Census Bureau 2021b). The resulting first cost as a percent of median household-income is shown in Figure 2. For the upgrades considered in Oshkosh, we use the 2020 median household income from Wisconsin (\$61,747) (“U.S. Census Bureau QuickFacts: Wisconsin” 2021).

For the average pre-1980s residence in Oshkosh, the ECM1 package costs ~US\$10,000 after federal and state subsidies when timed with required replacements and the ECM2 package costs US\$23,000 per residence based on RSMeans data (Berzolla 2021). The costs and payback period for each package for the two predominant archetypes in Oshkosh are detailed in Table 1.

Table 1. Cost and payback period for the ECMs in residences in Oshkosh, WI.

Archetype	Energy Efficiency (ECM1)		Energy Efficiency + Heat Pump + PV (ECM2)	
	Cost	Payback (years)	Cost	Payback (years)
Pre-1980	\$10,000	10	\$23,000	15
Post-1980	\$8,700	5.5	\$22,000	10

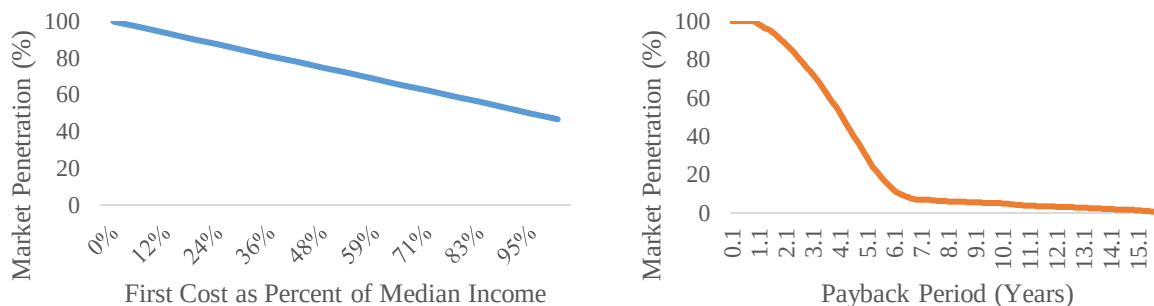


Figure 2. Arthur D. Little market penetration by first cost normalized by median household income (left) and payback period (right). Total penetration is determined by multiplying the two factors together. *Source:* Glesk 1979.

The predicted market penetration percentages from the graphs in Figure 2 are multiplied together to give a total market penetration for each upgrade, as shown in Table 2.

Table 2. Market penetration predicted by the Little model for the upgrade packages

Archetype	ECM1	ECM2
Pre-1980	5%	1%

Post-1980	19%	4%
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Leveraging the Little model market penetration provides insight into the split in adoption between the two measures, assuming the 1.6% (1% effective) adoption rate for all upgrades to owned residence. For example, in pre-1980 residences, ECM1 is five times as likely as ECM 2 and thus the adoption rate is 1.33% for ECM1 and 0.267% for ECM2. The average adoption rates for all building types and ownership combinations are given in Table 3.

Table 3. Adoption rates in the various scenarios tested

Condition	Archetype	Upgrade	Adoption Rate
1% all buildings	Pre-1980 & post-1980	ECM 1	0.50%
		ECM 2	0.50%
1% all owned	Pre-1980 & post-1980	ECM 1	0.80%
		ECM 2	0.80%
1% with ownership and costs	Pre-1980	ECM 1	1.33%
		ECM 2	0.27%
	Post-1980	ECM 1	1.32%
		ECM 2	0.28%

For the “1% all owned” scenario, the mean home ownership rate across all of Oshkosh is 63%. For an effective adoption rate of 1%, the adoption rate in this scenario is 1.6%. For the “1% with ownership and costs,” the 1.6% adoption rate is split up based on the ratio of the predicted final market penetrations given in Table 2.

Results

The adoption model was run for 30 years to simulate the adoption of building retrofits through 2050, the year Oshkosh has set for its 85% emissions reduction goal. The three refinements for predicting adoption in the methods section are run and the results presented in Figure 3. In order to test model stability, the simulations were run through 100 iterations leading to the mean emissions shown in Figure 3. In all scenarios for all years, the standard deviation never exceeded 0.31%. To show total technology pathway potential in 2050, reference lines for 100% adoption of ECM2 and ECM2 only in owned homes are included in Figure 3, as well as Oshkosh’s emissions reduction goal.

Each scenario leads to a notable outcome in Figure 3. In the 1% all buildings scenario, only half of the city’s emissions reductions come from building retrofits themselves, with the other half coming from the decarbonizing electric grid (which experiences a 55% decrease in emissions by 2050). Furthermore, this scenario is the most optimistic of the three in terms of emissions reductions, with the two additional scenarios predicting lower emissions reductions. The 1% all owned scenario parallels the 1% all buildings scenario but in the long-term (beyond 2050), the emissions reduction will be lower because the pool of eligible buildings is smaller. Another profound but expected result is the 1% with ownership and costs scenario leads to the smallest amount of emissions reductions of all three scenarios. This occurs because homeowners are a lot more likely to pick ECM1 than ECM2 and ECM1 only leads to an average 31% emissions reduction per home compared to an average 85% emissions reduction per home for ECM2. In all three scenarios considered in this analysis, **the predicted emissions reductions in 2050 do not come close to approaching Oshkosh’s 2050 emissions target or the theoretical**

maximum for each pathway investigated. It is especially clear from Figure 3 that higher adoption rates will be necessary if Oshkosh is to meet its emissions reduction goals.

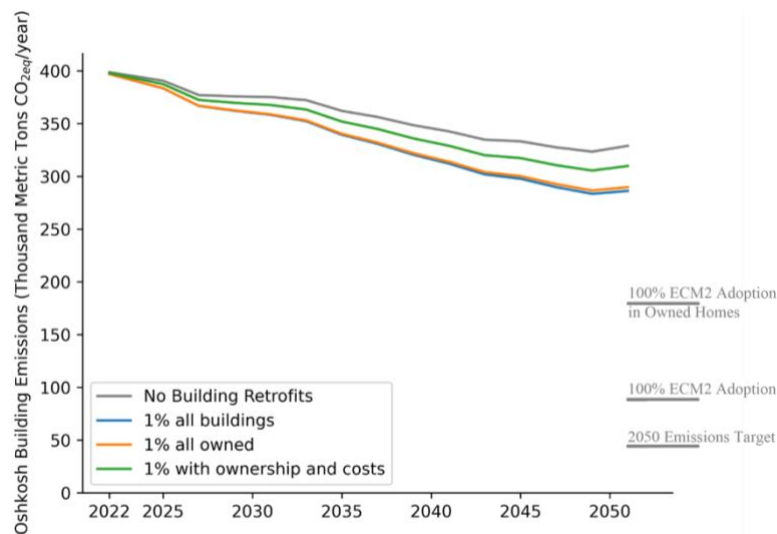


Figure 3. Emissions results for the Oshkosh case study with different adoption scenarios. The results presented are the mean for each scenario over 100 stochastic runs. The standard deviation envelope never exceeds 0.31% and is thus not shown. The 1% all owned and 1% all buildings scenarios fall within the envelope of one standard deviation.

The other glaring issue in Figure 3 is that even 100% ECM2 adoption in owned residences leaves a full third of the buildings (and emissions) in the baseline (non-retrofit) state. If this gap is addressed, the theoretical maximum of 100% adoption of ECM2 shown in Figure 3 can be reached. While this is not quite enough to meet Oshkosh's 2050 goal, there is less than a 10% emissions reduction remaining to get to the 2050 goal. This differs slightly from the results in Figure 1 because the significantly lower emissions factor for the grid in 2050 compared to the fixed value used in the previous study means PV offsets less of the remaining natural gas emissions (mainly for domestic hot water, the electrification of which was not addressed in the original Oshkosh study) than originally predicted. Since the PV capacity simulated in ECM2 only takes up about 50% of the rooftop area of the residential buildings, the overall renewable energy generation could be increased as needed to meet the remaining emissions reductions.

Looking only at overall emissions reduction will not lead to an equitable decarbonization future. The three scenarios examined in this study paint disparate pictures when it comes to the spatial distribution of upgrades and which upgrades occur. By assigning the predicted retrofit status in 2050 to the original buildings in an UDEM, we can see the fraction of buildings upgraded in each census block. In Figure 4, the 1% all buildings scenario, the retrofits are evenly split between the two ECM packages. The mean percent of residences upgraded per census block is 27% and upgraded buildings are fairly evenly distributed between blocks with differing WAP-eligibility, as seen by most blocks falling into the 25-30% category. The minimum percent retrofitted in any block is 18%, while the max is 35%. We use WAP-eligibility as a proxy for income in this analysis. In Figure 5, the 1% all owned scenario, the inequity in terms of which buildings are upgraded becomes apparent. The lowest percent of residences upgraded per block (0% to 5%) occur in blocks with the highest WAP-eligibility (62% - 91%). Meanwhile, the highest percent of retrofits (35% - 40%) occurs in blocks with the lowest WAP-eligibility (11%

and 17%). Furthermore, the minimum retrofitting rate falls to 5% and the maximum is 37%. In Figure 6, the 1% with ownership and costs scenario, nearly all retrofits are to ECM1 because of its lower cost and faster payback period compared to ECM2. This leads to the lower overall emissions reductions seen in Figure 3. The equity impacts mirror but enhance the 1% all owned scenario, with the lowest percentage of retrofits in the lowest income blocks. Consequently, the more realistic 1% all owned and 1% with ownership and cost scenarios show that residences in lower-income census blocks are left behind compared to other parts of the city.

1% All Buildings

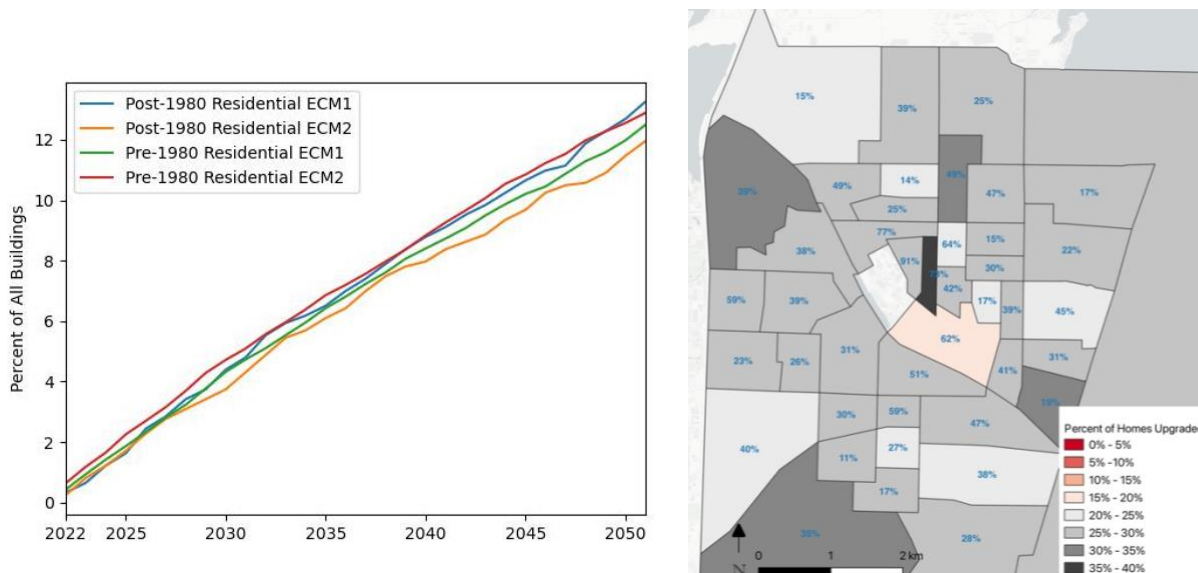


Figure 4. Building retrofits per year (left) and spatial adoption prediction in 2050 by census block (right) for the 1% *all buildings* scenario. Each census block is color-coded by the percent of residences upgraded by 2050 and labeled in blue text with the percent of WAP-eligible residences per census block.

1% All Owned

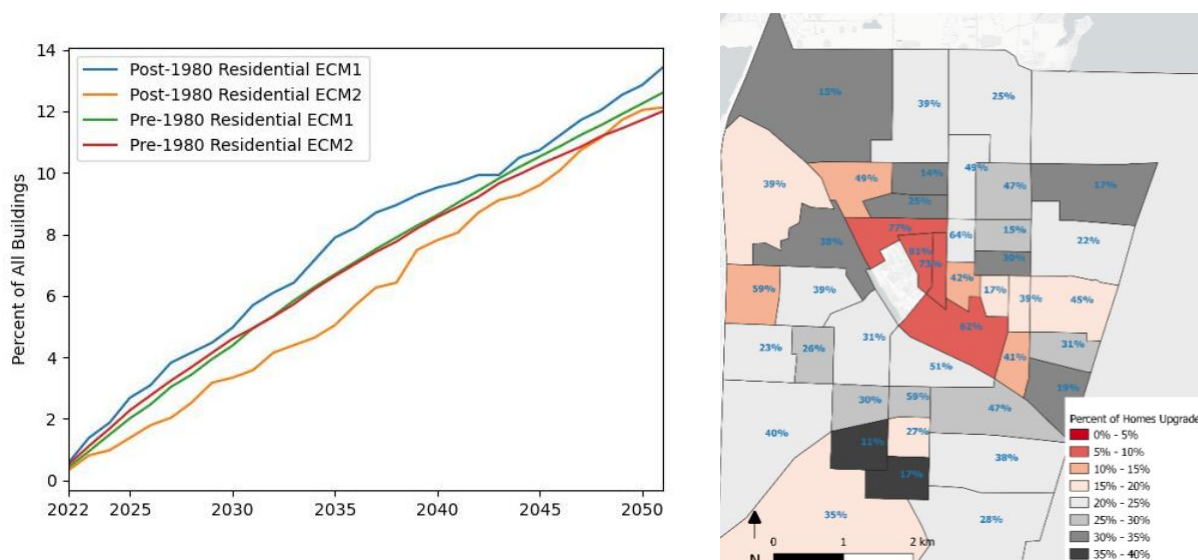


Figure 5. Building retrofits per year (left) and spatial adoption prediction in 2050 by census block (right) for the *1% all owned* scenario. Each census block is color-coded by the percent of residences upgraded by 2050 and labeled in blue text with the percent of WAP-eligible residences per census block.

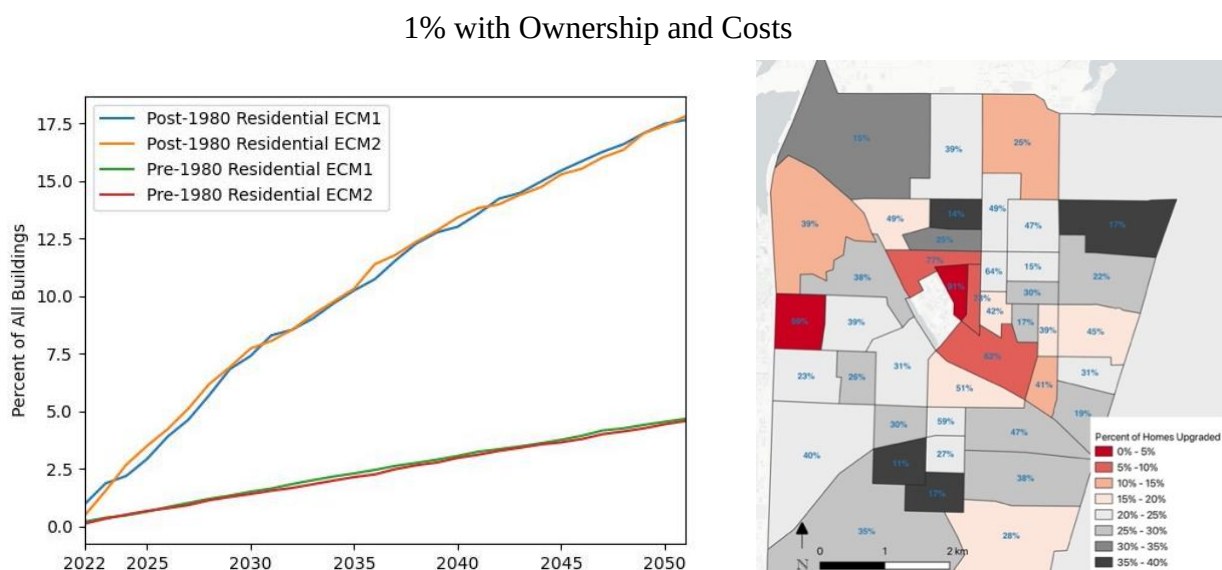


Figure 6. Building retrofits per year (left) and spatial adoption prediction in 2050 by census block (right) for the *1% with Ownership and Costs* scenario. Each census block is color-coded by the percent of residences upgraded by 2050 and labeled in blue text with the percent of WAP-eligible residences per census block.

Discussion

The Intergovernmental Panel on Climate Change (IPCC) argues that buildings will play a pivotal role in meeting global emissions reduction targets, estimating that the emissions of existing residential buildings can be reduced by 50% to 75% in many geographical regions (Intergovernmental Panel on Climate Change 2014). The analysis in this paper confirms that current adoption of building retrofits is far too low to achieve anything near the technically feasible technology pathways that would get a city to its emissions reduction goals. The retrofits that do occur, especially when costs and ownership are considered, are ECM1 packages that are inadequate to meet ambitious emissions reduction goals. Furthermore, the mutually exclusive nature of ECM1 and ECM2 leads to disparate future outcomes. Homeowners who continue to install the natural gas furnaces in ECM1 lock in natural gas infrastructure for the foreseeable future. Additionally, the cost of maintaining the aging natural gas distribution infrastructure to supply the furnaces will fall on these homeowners who cannot afford to install ECM2 (or do not own the residence) and must remain connected to the gas utility. Beyond the financial and climatic harms represented by this pathway, these homes will continue to be affected by the adverse health effects of gas appliances, further exacerbating health issues amongst lower-income populations (Lebel et al. 2022).

It is well documented that low-income – as well as Black, Hispanic, and Native American households – have household energy costs that are a greater proportion of their income (~8% to 10% compared with ~2% for the average household), with studies suggesting that low-income households face three times higher energy burdens than other households (Drehobl, Ross, and Ayala 2020; U.S. Department of Energy 2018). Many of these households are eligible for the

U.S. Department of Energy's WAP program, which in theory provides a low-to-no cost home retrofit to homeowners. Unfortunately, the 25% average energy savings from a WAP project is far lower than the 38% energy savings from ECM1 or the 62% energy savings of ECM2 in this analysis (U.S. Department of Energy 2021). When you further consider that Blacks, Hispanics, and Native Americans own homes at 25% to 30% lower rates than non-Hispanic white homeowners, the discriminatory nature of energy burdens becomes clear (Edelberg et al. 2021). It is therefore crucial from both an equity and an emissions reduction standpoint that cities have a strategy to ensure their rental buildings are also retrofitted to the necessary standards. By presenting data on the loss in emissions reduction potential when rented residences are excluded, policymakers can justify new ordinances that target rental efficiency measures specifically, such as the one passed in Burlington, VT in 2021 (*Burlington Code of Ordinances, Chapter 18: Housing* 2022). There are only a handful of municipalities that have enacted such legislation and this framework is meant to help address this glaring issue most cities face in meeting their emissions reduction goals in the built environment (Glassman and Ayyagari 2021).

The mapping of adoption by block group with key demographic data such as WAP-eligibility used in Figures 4, 5, and 6 is a crucial tool for city decisionmakers trying to pursue equitable decarbonization of the built environment. These maps – which can be created at different granularities – will be helpful for city decisionmakers trying to roll out programs that change the way building retrofits are adopted, by targeting specific areas of a city. For example, decisionmakers can focus on areas that have high WAP-eligibility and low predicted upgrade percentages. This kind of targeted outreach will likely be necessary to raise adoption rates.

The fixed adoption percentage per upgrade is the weakest link in this analysis. In reality, the adoption rate will vary by time, especially as more retrofits are completed and the uncertainty around payback, implementation, and other factors decreases. There is a vast literature on the diffusion of innovation but to the authors' knowledge this has not been studied in the built environment. The Little model for market penetration is the most extensive information on the market penetration potential but has no information on the pace of retrofits. The fixed adoption rate approach in this paper provides the most realistic picture possible today about where and what building retrofits occur given the limited information available. In the future the authors hope to improve these predictions with a diffusion model, but parameterizing this will require further study and surveys, such as those used by Dong and Sigrin (2019) to better understand homeowners' willingness to pay for building retrofits. As better adoption rate predictions based on income are developed, this framework can help decisionmakers get the most out of the resources they devote to supporting retrofits by enabling them to target only the residences that would not otherwise pursue retrofits or only pursue ECM1 and instead get them to pursue ECM2, stretching limited funding even further.

Conclusion

Information about building retrofit adoption is crucial to communities trying to achieve their emissions reduction goals in the built environment. Most analyses today assume buildings will automatically be retrofitted as technology improves. The framework presented in this paper provides key decisionmakers with an understanding of where buildings retrofits will naturally occur and under what financial parameters, so they can target programs to support adoption towards buildings that would otherwise not participate. This framework not only provides decisionmakers with the temporal accompaniment to their emissions reduction goals, but it also provides them with the ability to target programs that support higher rates of building retrofit

adoption and address the longstanding inequality in the built environment. While net zero emissions reduction goals in most municipalities are physically feasible if deep energy retrofits are implemented and the grid decarbonizes, the current retrofitting rate of 1% is not nearly enough to achieve the full technical potential by 2050, when most communities' net zero targets are set. Furthermore, when we account for more realistic adoption based on building ownership and retrofit cost, the actual adoption rate and therefore emissions reduction drops even further. When accounting for these crucial factors, the distribution of retrofits is clearly unjust, disproportionately occurring in high-income, high-ownership areas of a city. While it is not surprising that retrofits are currently limited to wealthy homeowners, the disparity laid bare in this analysis should be a call to action for policymakers. Cities around the world need to address the inequity in the adoption of building retrofits while also greatly expanding support to all retrofit projects to drive higher adoption rates of more comprehensive retrofit packages that will put communities on target to meet their emissions reduction goals. Ultimately, the results presented in this paper are a more realistic baseline for how emissions reductions in the built environment will play out in most communities. The framework presented here can and should be used by communities around the world looking to equitably achieve their GHG emissions reduction goals.

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