RETROFITTING FOR RESILIENCE

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Abstract

This thesis explores the incentives and barriers to retrofit single-family and small multi-family homes in Boston, in response to the city's declared goal of reaching carbon neutrality by 2050 while protecting citizens from extreme weather events induced by climate change. Considering small properties do not report their energy consumption, little is known about a sector that accounts for 20% of the city's carbon emissions. The federal, state and local government offer a myriad of incentive programs to improve the energy efficiency of these homes, yet uptake on those opportunities is low and inconsistent with the rate needed to achieve the city's mitigation and adaptation goals.

Recent technological advancements enable the study of these buildings from the ground up, enabling urban scale insights from the study of individual buildings' performance. The methodology to develop Urban Building Energy Models (UBEM) was developed by the Sustainable Design Lab at MIT in 2016, to estimate citywide energy demand loads down to the individual building level. Utilizing an existing UBEM for two neighborhoods in Boston, this thesis explores the impact of energy savings and government incentives on households' ability to participate in retrofit programs, to uncover unmet needs and form recommendations to accelerate retrofit implementation. The novelty of this research is not in developing the model, but in exploring a new application of an existing model.

Results show that while implementation of retrofits is not financially beneficial for every household, there is a substantial gap between the number of households who can potentially benefit from these incentives and the current participation rate. Interviews with policy designers and architects working on retrofit implementation in Boston reveal additional barriers to explain this gap. Recommendations for quick fixes include better visualization tools to communicate the specificity of applicable programs at the individual building scale and in response to the householder needs, investment in programs to bolster communities' organization capacity and expediting and streamlining the process to make it easier to access.

This study demonstrates the potential of UBEM to inform public policy and increase citizen access to government benefits, as part of a global effort to enhance the transparency and the efficacy of governance through digital interfaces.

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Thesis Reader: Eric Robskey Huntley

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It has been my honor to participate in this research, and just like I was able to follow others' footsteps, I am excited to find out what will come next.

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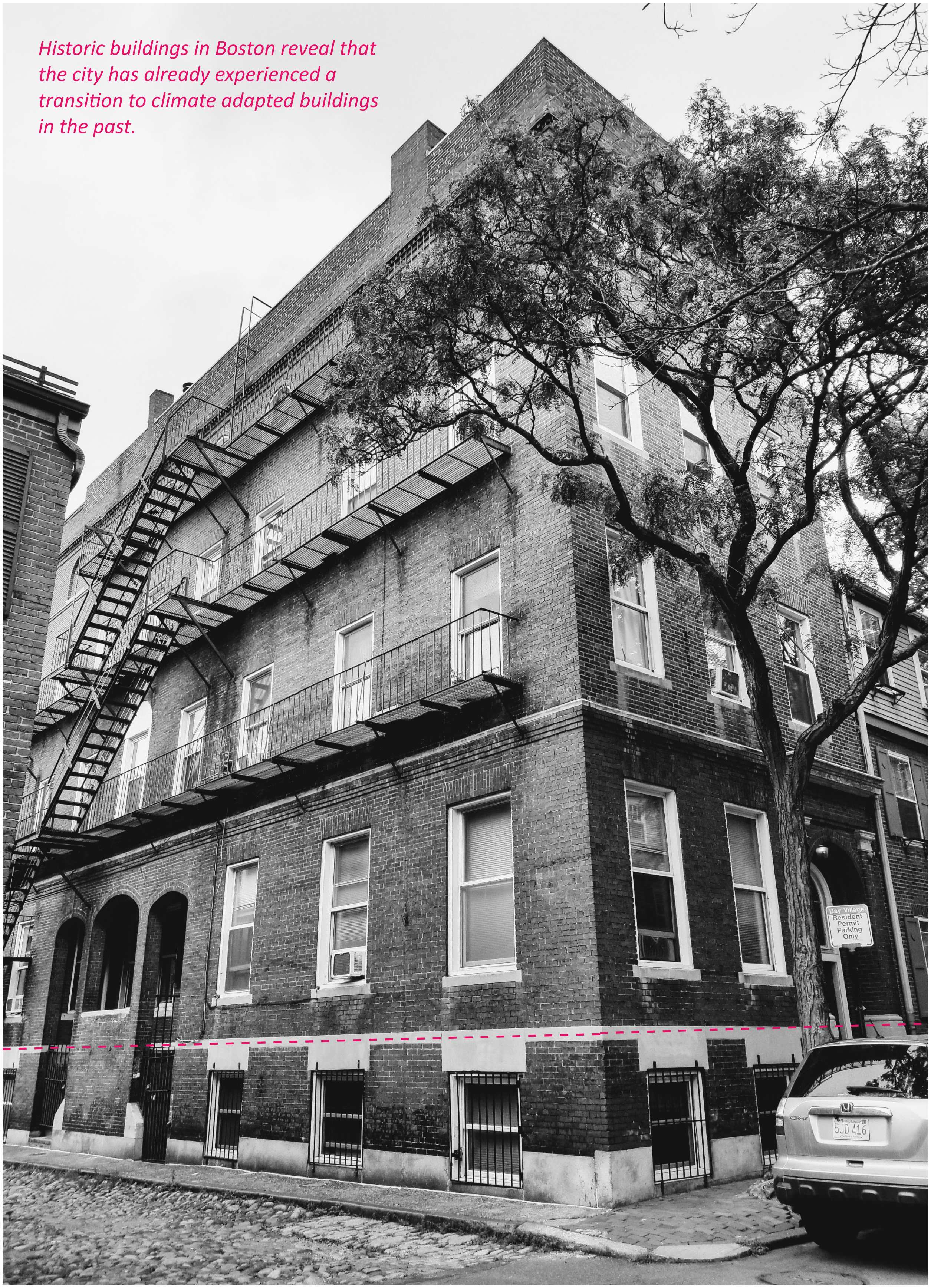


Historic buildings in Boston reveal that the city has already experienced a transition to climate adapted buildings in the past.

01 Introduction: Retrofit For Resilience

Retrofit for resilience is a call for an equitable transition to low carbon homes

Considering the multi-function buildings provide, energy efficiency and climate adaptation renovations must address the social function of buildings as well as their physical infrastructure function. Retrofit for resilience is not just about flood-proofing or replacing a furnace; it is about the overall ability to provide urban dwellers with streamlined, hustle-free, and financially sound options to implement whole-building retrofits. In the context of climate change and buildings, public policy must address both infrastructure resilience and social resilience to respond to climate, justice and health challenges.

The urgency of rapid action to reduce carbon emissions before 2030 is outlined in the 2018 Intergovernmental Panel on Climate Change (IPCC) report. It is described as the only way to limit global warming to 1.5oc above pre-industrial levels and avoid the risk of cost escalation, lock-in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options[1]. A previous IPCC report on buildings revealed that buildings account for 32% of total global energy use and 19% of energy-related GHG emissions[2]. Buildings also absorb the impact of climate events, including damages due to sea level rise and extreme weather events. Therefore, addressing the challenge of retrofitting the existing building stock in cities is imperative in order to mitigate the impact of climate change as well as to improve urban dwellers' quality of life.

Since climate challenges are all encompassing, just distribution of public resources is essential to the success of meeting climate goals as well as to the ability to provide adequate service to citizens. If only people who have access to education and financing options will implement mitigation and adaptation measures in buildings, society will not meet carbon emissions reduction targets by 2050. Retrofit programs need to empower citizens, provide them with resources, and bolster their organizational capacity to improve the quality of their homes and offices while meeting climate goals. Beyond the practicality of reaching the largest audience, just distribution of resources provides dignity, compassion, and a compelling invitation to participation.

Lastly, retrofitting buildings also has a significant impact on public health. Buildings containing hazardous materials, limited natural ventilation, and antiquated Heating, Ventilation, and Air Conditioning (HVAC) systems have adverse effects on indoor air quality and public health. Application of energy efficiency measures without considering health impacts can either perpetuate or exacerbate the detrimental long term effect of poor indoor air quality on people's health[3]. Therefore, the pathway to low carbon homes must include strategies to abate hazardous materials and improve indoor air quality.

Within this complex environmental and social context, this theis explores pathways to implement deep energy retrofits from a climate-justice perspective, seeking to understand how access to public resources simultaniously affects individuals' ability to participate in retrofit efforts and city-wide ability to meet climate adaptation and mitigation goals.

MOTIVATION

My interest in climate justice and the built environment is rooted in my education and professional work on sustainable and equitable development in the past ten years. Prior to arriving at MIT, I led the development of strategic plans to revitalize neighborhoods and cities, working closely with diverse urban stakeholders including community partners, architects, engineers, politicians, economists, developers, and government agencies. Observing how urban policies impact peoples' lives at a very intimate level, I have learned the importance of compassionate design, information transparency, and attention to detail, for truly providing communities with effective tools to improve the quality of life in their urban environment.

My particular interest in the retrofit ecosystem in Boston was developed during my fellowship with the City of Boston Environment Department in the summer of 2018. At the time, the Environment Department was working on updating its climate action plan and developing its carbon neutrality strategies. Impressed by the bold goals the Department was setting for the built environment, I was intrigued to learn more about the policies that will enable these actions, knowing that as a climate leader, successful policies in Boston can pave the path for other cities in the USA and possibly worldwide. It was serendipitous timing since my interests in studying retrofit implementation pathways were aligned with the City's interest in reviewing its existing policies.

Therefore, the motivation for this thesis is inspired both by Boston's mission to transition to low carbon buildings by 2050 and by my own interest in implementation pathways and the ability of all citizens to participate and benefit from these efforts. I hope that the methodology to study these challenges and the findings of this thesis will be useful for the city of Boston Environment Department, as well as for other cities facing similar climate justice challenges.

RESEARCH GOAL

This thesis explores the ability to study neighborhoods' retrofit potential from the ground up to simultaneously provide policymakers with evidence-based insights into the design of retrofit programs, and provide urban dwellers with practical information about the specificity of retrofit incentives available at the individual building scale.

Focusing on the retrofit ecosystem in Boston, this thesis explores the incentives and barriers to retrofit small multi-family and single-family homes in Boston to understand why participation in retrofit programs is low despite a myriad of government incentives. By studying the impact of location, building type and household type on the ability to participate in retrofit programs, this thesis aims to shed light on the impact of affordability and access to government benefits on the neighborhood's ability to meet carbon neutrality targets.

In a broader scale, this thesis responds to the IPCC (2018) call to bridge the knowledge gap about mitigation in buildings. Previous research has established what energy efficiency and energy generation measures are needed to transition to low carbon buildings. This research explores the ability to implement those measures at an urban scale.

CONTEXT: BOSTON

This project-based thesis focuses on the city of Boston since it is a climate leader at a global scale, committed to carbon neutrality and adaptation goals by 2050.[4] Currently, the existing stock of buildings accounts for 71% of greenhouse gas emissions[5] and is also under different risks of flooding. 2016 projections estimate that by 2050, 7% of the total land area in the city could be exposed to frequent stormwater flooding from 10-year, 24-hour rain events.[6] Over the past three years, the City accelerated its climate research and boosted its outreach programs. In 2016, the

City completed a comprehensive climate risk assessment and is currently following up on this plan by developing neighborhood resilience plans in partnership with local citizens. In 2019, the City completed a city-wide assessment of carbon emissions and energy efficiency by sector. This research is communicated to the public through the Environment department public outreach initiative *'Greenovate',* which raises awareness to environmental concerns and supports the empowerment of Bostonians through the climate leaders program. Put together, the accumulating research and awareness positions Boston in a unique place to make informed decisions about its future climate policy and implementation pathway.

At the same time, Boston faces many challenges to meet its ambitious 2050 targets. Since different federal, state, and municipal departments are responsible for climate and social policies, each concern is addressed separately, creating confusion over the resources available for buildings' retrofits. To add to the confusion, each retrofit project requires multiple stakeholders to form agreements. Collaboration is needed between the city which permits and incentivizes projects, homeowners and renters who use the buildings, neighbors who live nearby, and developers/contractors who can implement large projects. Due to these frictions, the current process of retrofitting buildings is not advancing at the desired pace, limiting Boston's ability to achieve its 2050 targets.

OUTLINE OF METHODS AND FINDINGS

This research utilizes interviews, policies review, and data analysis to study the current state of retrofits in Boston at the single building level.

The interviews and policies review provide insights into the existing programs, regulation and financing tools to encourage retrofits, and into the experience of policy designers, architects and developers with retrofit implementation in Boston. Together they illustrate the opportunities and barriers for the major stakeholders who participate in the process and help identify knowledge gaps. Following these interviews, targeted data analysis was conducted to address existing knowledge gaps with regards to the ability of people living in 1-4 family homes to participate in retrofit programs.

The methodology to provide a city-wide energy model from aggregated analysis at the single building level was developed by Christoph Reinhart and Carlos Cerezo Davila at the Sustainable Design (SD) Lab at MIT, to expose the impact of energy efficiency measures on a city's total energy consumption.[7] Since 2016, this methodology was implemented in several cities worldwide to provide decision-support for energy efficiency and energy generation policies. Using a UBEM developed by Jamie Bemis[8] and Ali Irani[9] from the MIT DS lab for Dudley triangle and the South End, this research adds a new workflow to map federal, state and municipal incentives by parcel, and to explore whether the incentives and energy savings can offset the retrofit cost. Aggregated results at the neighborhood scale reveal the impact of affordability on the city's ability to meet its 2050 carbon neutrality target.

The research concludes by using insights from the data analysis and the interviews to explain the gap between the potential to retrofit and actual participation and recommends future steps to accelerate retrofit implementation in Boston.

02 Literature Review + Interviews

GLOBAL RETROFIT EFFORTS

The urgency of retrofitting cities at large in response to climate change is an unprecedented challenge.

On the one hand, some researchers call for more concentrated planning effort. Eames et al. argue that *"Large scale urban retrofitting requires systemic change in the organization of built environment and infrastructure, and the integration of socio-technical knowledge, capacity, and responses. It also requires new forms of knowledge, expertise and decision support systems that better integrate the technological, economic, and environmental issues and options and societal challenges involved in implementation."*[10]

On the other hand, traditional urban planning and design tools to envision changes to cities or large areas in cities rarely achieve their targets. Observing this phenomena, Ryan describes the principles that are inherent to urban design as incomplete, change and lack of fidelity, to argue that unitary large-scale urban design processes are not appropriate tools for the task they are used for. Instead, Ryan calls for a 'Plural urbanism' as an art that is *"appropriate for the city that is, rather than one that waits for the city that may never be"* [11].

So how can cities mobilize towards a more sustainable future?

In contrast to urban design approaches that mandate change through zoning and regulation alone, emerging tools to address climate change challenges use a mixture of regulation, incentives, and public outreach to encourage individuals and communities to make more sustainable choices regarding their properties. This section will open by describing key market challenges to retrofit implementation and continue by exploring how cities worldwide respond to these challenges, highlighting the difference between market-based, regulation-based, and community-based approaches.

Studies of the market's response to the energy efficiency challenge find that there is a gap between the availability of energy efficiency technologies and their adoption rate by consumers who can financially benefit from them. Gerarden et al. (2017) refer to this gap as the "energy paradox" and to the broader phenomenon of lack of adoption of technologies that would be socially efficient, they refer to as the "energy efficiency gap". Both represent a contrast between private and social optimality, which ultimately has important implications for the role of various policies, as well as their expected net benefits.[12]

From the real estate perspective, Chegut et al. (2017) argues that incentives to innovate from a financial perspective are not necessarily linked back to the innovators themselves, which inhibits the research and development sector which designs the buildings and technologies that enable green buildings. Additionally, they add that another barrier to the diffusion of green building technologies can be caused by the difference in social and financial incentives between the stakeholders who implement innovations. And lastly, due the complexity of buildings, there is limited ability to achieve return to scale.[13] Thus, market failure, behavioral effects, and split incentives act as barriers to the implementation of energy efficient technologies.

To address these challenges, local governments in cities are currently developing policies to accelerate retrofits of the existing building stock and forming networks for peer-learning and knowledge exchange. Boston, along with 96 of the world's largest mega-cities participates in the C40 initiative for municipal climate leadership. These cities are committed to take bold climate actions and share their knowledge and experience with others.[14]

Research completed in 2016 into innovative policy practices to advance building energy efficient retrofitting in 10 C40 cities in USA and Asia-Pacific, identified the following overarching approaches: Mandatory Benchmarking, Periodical energy efficient auditing or retro-commissioning, Energy efficient standards, cap and trade, voluntary capacity building and friendly competition. While these approaches are distinct, many cities are combining several approaches, in particular the first three.[15] Common to most of these approaches is the mission of building a transparent database for buildings' energy efficiency and using that information the leverage different policies.

One of the best examples for using benchmarking data as a platform for knowledge exchange is New York City's Retrofit Accelerator initiative. This program was created in 2015 by NYC Mayor's Office of Sustainability, to identify and assist privately owned buildings in implementing energy efficiency upgrades. The online platform offers free, personalized advisory services that streamline the process of making energy efficiency improvements to building that will reduce GHG emissions, operating costs, and enhance tenant comfort.[16] In addition, using information collected through the City's building energy laws and other city datasets, the efficiency advisors were able to determine which buildings would be the highest priority for assistance and target their outreach Based on their experience in the first year of the project, the Efficiency Advisors found high latent demand for solutions to fix heating distribution problems among owners and decision makers of NYC buildings. Since addressing this issue will yield significant GHG reductions, they launched a targeted campaign for steam heat in 2016. By November 2017 they identified and engaged with 5,000 buildings, among them over 1,600 projects are either in construction or complete. Another advantage of the campaign was to generate demand for green technologies projects.[17] While NYC Retrofit Accelerator is a very new initiative, initial findings show great promise in using individual building data to create targeted climate programs to bridge information gaps.

In contrast to approaches that target individual property owners as an agent of change and considering a smaller housing scale, UK researchers emphasize policies that enhance the various relationships among retrofit actors as well as their specific contexts in new and generative ways through community-based retrofits. These programs share some commonalities. First, the occupants are at the center of decision-making processes, so that retrofit planning efforts can take into account how the property is physically configured and used. This input is essential for developing long-term solutions that respond to residents' needs. Second, the retrofit process considers technical and economic issues but also social issues related to comfort, health, wellbeing, and happiness. Thus providing a more compelling reason to participate, other than energy efficiency.

One example of the local governance of retrofit is the Carbon Coop, a member-owned community benefit society in Manchester that represents over 100 households. In addition to traditional government incentives, the organization secured £500,000 in funding to retrofit 12 houses across Greater Manchester. Using both funding sources, they practiced whole house retrofit by strategizing with homeowners on multiple measures to reduce carbon emissions by 80% or more while also being affordable.

Another example for community retrofitting is 'Retrofit for the Future', a £17m program launched in 2009. The project lowered the carbon emissions of 86 houses by 50–80% through the purposeful coordination of housing providers, designers, contractors, and researchers. They identified four keys to successful retrofit: project planning; site management; understanding the supply chain; and working closely with residents.[18] These relatively small scale projects reveal approaches that target behavior barriers.

Operating at a larger scale, the Israeli earthquake resilience policy also sees retrofitting as a communal effort and seeks to align interests for the different stakeholder involved. Since it was enacted in 2005, over 30,000 earthquake resilient housing units have been created, the majority of which in big cities where financial benefits are maximized.[19] The policy provides value to developers through tax exemptions, process accelerations and ability to add additional density which can be sold for profits[20]. In return, developers manage the entire retrofit process at no cost the property owners. When the process is complete the buildings are reinforced and renovated, thus enhancing the city's safety and urban design. The overall success of this initiative attracts criticism for failing to consider the overall impact the added density has on urban services and effect on renters.[21] In this example, public incentives to the private sector create the market for retrofits and these private actors take on the responsibility of reaching out to property owners and managing the process from day one to completion.

Lessons from the experience of cities worldwide with retrofit implementation reveal several common threads. First, a shared understanding of the challenge and collaboration between the different actors is key to success. Second, a dataset that identifies where the action is needed can stir both the public and private sectors. Third, effective communication with all stakeholders encourages participation. Overall, these tools provide a platform for the different stakeholders to act on personalized information regarding participants' opportunities to benefit from action. By doing so, they enable a more plural decision-making process, while also providing socio-technical knowledge.

Within this context, this thesis seeks to create a decision support tool to provide individuals with the information they need to make an informed decision about retrofit implementation and to provide policymakers with the information they need to identify barriers to implementation and restructure policies so that they can reach their target audience. Advances in technology, which are further discussed in the methodology section, enable the study of the urban building stock at the individual building level. Previous research established that access to information at the single building level can empower property owners and other stakeholders to implement energy efficiency measures.[22] Together, advances in analysis, technology, and communication, coupled with the urgency of responding to climate change, enable a new kind of city-making that doesn't emerge out of a masterplan, but nevertheless aims to change the urban fabric profoundly.

BOSTON'S RETROFIT EFFORTS

During January – March 2019, I conducted interviews with 20 professionals who hold leadership positions in the public and private sector and have extensive experience with retrofitting buildings in Boston. Interviewees were asked about their experience with policies to incentivize retrofits and home improvements in Boston, with the goal of mapping the existing possibilities and barriers to implementation. The following section summarizes insights from these interviews and policies reviewed, organized under four overarching themes: state energy policy, zoning & regulation, urban design, and organizational capacity.

STATE ENERGY POLICY

As the capital of Massachusetts, Boston benefits from the state's progressive energy policies, that have positioned it as the most energy-efficient city in the U.S by the American Council for an Energy-Efficient Economy (ACEEE) since 2015[23]. MA most renowned program, Mass Save[24], is a utility mandated rebate program to assist the implementation of energy efficiency measures. It provides targeted incentives per energy conservation measure including insulation, HVAC system upgrade, appliances upgrades, and lights upgrade. It also provides special assistance to low-medium income populations and a 0% loan financing program for 84 months up to $50,000. The first step to engage with this program is through an energy efficiency audit, where a Mass Save contractor can also replace all lights to LEDs and seal drafts at no cost to residents.

Mass Save is made possible by two primary policy instruments: 'decoupling' and 'system benefit charges'. The first policy instrument, 'decoupling', is a mechanism that disconnects the revenue of utility companies from the amount of energy sold, thus incentivizing them to support efficiency. it is derived from the proces of decouplong the volumetric sell of KW hours from the overall compensation that's regulated by the state for the provision of electrical services. The second policy instrument, 'system benefit charges', is a fixed rate on all utility bills all Massachusetts residents pay.

Along with the tremendous success of this program across the state, there were unintended consequences for urban dwellers with barriers to entry. Bradford swing, Director of Energy Policy and Programs in the City of Boston reveals that

"Boston ratepayers were paying more into the state-wide programs than they were getting back because of the difficulty in connecting energy efficiency to urban building types and residents."

In other words, People who do not live in an owner-occupied single-family home with enough resources and time to follow a complex multi-step process, have higher barriers to entry. Thus, people who live in multi-family buildings, renters, non-native English speakers are paying for a service they do not receive. To address these challenges, Boston initiated the Renew Boston outreach program, which is discussed in the following organizational capacity section.

The current structure also enables private companies to collect a considerable amount of money from the public, without any obligation to be transparent about how that money is used. Swing emphasizes that this is a constraint of the ability of public servants to improve service to citizens, in particular when it comes to limited ability to measure the quality of investment in outreach programs and consumer satisfaction.

To conclude, Massachusetts successful energy efficiency programs are not sufficiently adopted by Boston's residential and commercial sector, leading to overall citywide revenue loss. Moreover, without transparency about how system benefits charges are used, it is difficult to successfully intervene to increase adoption rates.

ZONING & REGULATION

The City of Boston supports the creation of a resilient building stock through regulation to ensure new projects are built to meet high environmental standards, and regulation to ensure substantial renovation projects comply with resilience standards.

Since 2007, every new project has to comply with article 37 in the zoning code, which requires all projects to achieve at minimum the 'certifiable' level utilizing the most appropriate US Green Building Council Leadership in Environmental and Energy Design (LEED) Rating System(s). Also, through the resilience policy checklist, buildings have to consider present and future climate conditions in assessing project environmental impacts, including carbon emissions, extreme precipitation, extreme heat, and sea level rise.[25]Furthermore, the city is also promoting the generation of energy positive buildings through the E+ initiative that was created in 2011, and since then have been implemented in several sites for new development.[26]

While these initiatives set Boston on a promising path towards ensuring new buildings are climate adapted, some of the interviewees commented that the minimum LEED requirements are not sufficient to support the ambitious carbon emissions mitigation goals that the city has committed to in the recent Carbon Free Boston report (2019). In particular, interviewees were concerned that the quality of insulation could be better and that energy choices other than electricity are still contributing to an increase in the city's carbon emissions.

With regards to existing properties, the City started regulating properties that are 35,000sqft or larger in 2014, through the Building Energy Reporting Discloser Ordinance (BERDO)[27]. This ordinance mandates annual reporting of energy consumption, with a requirement to either show an improvement every 5 years or to perform an energy audit. Program manager Benjamin Silverman reports that the current compliance rate for 2018 of 90% by square footage has been achieved without enforcing a penalty mechanism. At the same time, 2019 marks the first deadline to either show improvement or to perform an audit, and many property managers were unaware of this requirement. Moving forwards, Silverman identifies four challenges for implementation. First, a robust data set is needed to support policy design. However, data collection has been inconsistent previously, and it may be difficult to access or analyze data received in the earlier years of the program. Second, the audit requirement does not mandate any action. Thus properties who performed audits in 2019, are not required to follow through on the audit recommendations before 2024. Third, the enforcement mechanism is insufficient, and it is a concern that it may be easier for some properties to pay a fine and be non-compliant rather than to implement energy efficiency measures. And fourth, financial incentives for large properties through Mass Save, the utility mandated rebate state program, has focused on in the past 'low hanging fruits' such as LED lights and at times hasn't offered sufficient assistant for more significant deep green retrofits Other than benchmarking through the BERDO initiative, is no regulation to mandate resilience/ energy efficiency upgrades.

Once building owner/s decide to perform a renovation project, they will follow either the long or short review process, depending on property size and type of renovation. Any major renovation that exceeds 50,000sqft or involves more than 12 units will trigger the article 80 review process. This extensive review process requires planning and design documents signed by a licensed MA design professional to ensure the renovated project complies with the current state building code and local zoning ordinance. In some cases, the review committee might ask for a community review process that might further extend the permitting time. As part of the review process, the applicant must consult with relevant departments and receive their approval, for example, changes to the exterior of the building in a historic district necessitate review by the Boston Historic Building Commission.

Experienced architects working on retrofitting existing buildings in Boston share that the permitting process is long and complex with a different process for review and permitting. In some cases, getting old buildings to comply with the state's building code for fire and safety or the Americans with Disabilities Act (ADA), can be cost prohibitive and dissuade developers from moving forward. In other cases, developers may choose not to apply for the historic conservation tax credit because the regulations to comply are more expensive than the returns through the tax credit.

In contrast, the process to approve minor alterations that do not impact the structural integrity of the building or the number of occupants can be processed within a short time of 1-2 days. Such changes include insulation and window replacement with no change to the window size (in buildings outside the historic buildings overlay), as well as HVAC upgrades. This type of renovation is typical for small scale residential retrofits.

1-3-unit family homes also have the option to participate in the Additional Dwelling Unit (ADU) initiative, which aims to develop more housing options while creating rental income for homeowners.[28] The program is an excellent example for a multi-agency collaboration between the mayor's office for New Urban Mechanics to bring insights about financing and housing supply, the BPDA to provide design guidelines and the Inspectional Services Department (ISD) to streamline and expedite the procedure, wave FAR, parking and zoning considerations.

The program enables 1-3-unit family homes owners to add an ADU within the envelope of their existing building (utilizing either the attic or the basement) and provides access to a 0% loan up to $30,000. Attorney Kim Thai, who serves as the Assistant Commissioner of Plans and Zoning and the Director of Policy at the ISD, explains one of the goals this program aims to achieve is preventing displacement.

In her words:

"with an older building stock, there are many cases where people have owned a property for many years, but now that housing costs have risen, they have no money to renovate. These people are then approached by developers to sell their houses and are being displaced".

In many of the applications Inspectional services received in 2018, the ADUs were requested to house children coming back from college and looking for affordable housing. Since enacted, out of a total of 61 applications, 31% passed review and are in progress to implementation.

The Department of Neighborhood Development who approves the loan requests, reveals that the mean cost of an ADU project ranges between $40,000-$50,000 non inclusive of architect fees. Thus, it is fair to assume that the early success of the ADU initiative is in supporting citizens who have additional financial means to supports costs above the loan limits.

Another example of a successful inter-agency collaboration for home renovation is the BREATH Easy at Home Program. This program is a partnership between the Boston Housing Agency (BHA), ISD, Boston Medical Center, and Community partners (parent asthma leaders), led by the Boston Public Health Commission. The program is a web-based referral system that lets healthcare professionals refer Boston residents with asthma for a home inspection conducted by ISD. ISD inspectors help Boston residents with asthma by working with property owners to address poor housing conditions that affect asthma and are violations of the Massachusetts Sanitary Code, including: mold and chronic dampness, leaks, pest infestations, drafty doors & windows, no heat, poor ventilation and damaged carpeting. [29] This program is a measure of last resort for tenants to force landlords to comply with sanitary regulation.

Darris Jordan, the program coordinator, works with the landlords to help them understand the process and to expedite implementation. In many cases, he acts as an intermediary between the landlord and the tenant and works to resolve the needed renovation without having to go to housing court.

URBAN DESIGN

Policy designers interviewed for this research indicated that there is no urban design plan to support retrofits for energy efficiency. Considering Boston's location by the sea, protection from climate risks dominate the planning and climate preparedness efforts. Following Climate Ready Boston's report in 2016, the City has initiated several climate adaptation plans to address flood risks in coastal neighborhoods, which identify landscape and engineering solutions to block flood paths and protect coastal neighborhoods. These plans outline public projects that will form the first line of defense against flood risks but do not address any particular actions that property owners need to implement as a second line of defense.

To complement the city-wide adaptation documents, both the environment department and the BPDA have issued design guidelines for private property owners, among them:

'Retrofitting Boston Buildings for Flooding: Potential Strategies' (BPDA, 2016)

'Boston Resilient Historic Building Design Guide' (Boston Environment Department, 2018).

These guidelines provide information about flood-proofing properties but do not address energy efficiency retrofits or financing mechanisms. In addition, the BPDA is currently in the process of developing resiliency guidelines for new construction and retrofits. These guidelines will address the most common building types that are in a flood overlay and provide them with the knowledge and tools for retrofitting. One of the options under consideration is allowing a density bonus as a financing mechanism to support retrofits.

ORGANIZATIONAL CAPACITY

Previous sections outlined the complicated multi-step process to retrofit implementation. This section outlines how program managers are tackling this issue to deliver sustainability goals for their sector, focusing on public buildings, affordable housing, and the small scale residential sector.

Starting with public buildings, the 'Renew Boston Trust' initiative[30], managed by the city of Boston Environment Department, is a long term program to increase the energy efficiency of municipal buildings. Program manager David Musselman applies a multi-phase approach to implementation. Strating with conducting analysis to identifybuildings that will benefit the most from retrofits. This process resulted in a list of 14 buildings out of 266 retrofit candidates. Next, each buildings underwent a Capital Needs Assessment (CNA) to balance energy conservation measures with costs. Following this cost-benefit analysis, Musselman established collaborations with other municipal departments to maximize the potential of the retrofit project and negotiated financing options and incentives with the utility companies. This process was supported by the city's ability to finance projects through bonds and hire a consultant company to identify buildings, implement energy conservation measure and measure results for 20 years. The Renew Boston Trust demonstrates the value of expert knowledge and negotiating power in retrofit implementation.

Another sector that benefits from effective management is affordable housing. Within this context, the Boston Housing Authority (BHA) is the greatest landlord in Boston, serving low-income population, earning 30% of Area Median Income (AMI) or lower, who live in some of the oldest buildings in Boston. Dan Helmes, the energy manager for the BHA for that past 18 years, was also able to hire engineers to perform energy audits and recommend cost-effective energy efficiency measures.

To finance this work, he uses a combination of HUD funding, energy savings based loans, and

Low-income Energy Affordability Network (LEAN) incentives. A similar financing mechanism was described by Tabetha McCartney, the Director of Asset Management and Sustainability at 2 Life Communities. McCartney also mentioned that since the low-income senior citizens who live in 2 life communities are not affected by the rent price (they pay 30% of their income and the rest is paid by the government), she was able to raise the rent and use the additional revenue to finance energy conservation measures.

When asked about barriers to implementation, Helmes indicated a need for more funding, assistance with cost prohibitive regulation, simplifying the rebates program so that returns are timely,not lower than investment and easy to apply for. In addition, since affordable housing residents do not pay utility bills, they sometimes do not understand the value of energy conservation measures, especially with fixed temperature thermostats set to a different temperature than they are used to.

Similarly, McCartney reported that residents who do not pay utility bills are disincentivized to conserve energy. In her experience, even after a deep retrofit has been completed, residents are likely to leave the windows open in the winter, keep the lights on if no one is in the room and replace water conserving fixture with less efficient ones. Another barrier to retrofit implementation was ensuring all residents have access to housing during the renovation process. To achieve this, McCartney used 'hosteling units' and movers that packed and unpacked a residents apartment and put everything in place down to the picture on the wall.

Lastly, the small scale residential sector is served by multiple programs administered by different agencies. The city of Boston provides two main programs to improve the housing quality of its citizens: the Renew Boston program[31], managed by the environment department and the Home Improvement program[32], managed by the Department of Neighborhood Development (DND). Currently, these are two distinct programs.

The Renew Boston program connects single family and small multi-family households with Mass Save resources. It was initiated in 2009 and was funded through grants from Eversource and National Grid to support community outreach, and a full-time utility liaison from Eversource who was housed in the Environment Department.   It also supported a full-time "Renew Boston Community Outreach Manager" who was initially grant-funded by two federal programs but became a later City of Boston employee.

Swing, who spearheaded the program at the time, dedicated substaintial efforts to coordination with the utility companies and community outreach including social media, mailing, postcard or letter invitation to a workshop on a Saturday or after work hours. Their ambition was to encourage residents to get an energy audit through Mass Save, with the hope that following the audit residents will be better informed and supported to implement energy conservation measures.

Former Renew Boston community outreach manager, Lourdes Lopez emphasizes that

"Renew Boston is not a marketing program; it is about connecting the pieces in a complicated puzzle."

She says that the strength of the program was in connecting people with resources from different agencies. For example, property owners who had difficulty to get in contact with Mass Save were able to rely on Lourdes assistance in expediting the procedure and connecting residents to the right resources.

According to Lourdes, populations who had high barriers to engaging with Mass Save for audits are non-native English speakers, people who could not take time off from work and renters. Among the people who received the audits' results, barriers to implementation of energy efficiency measures include deficient funding options, inability to take time off work to schedule improvements, and lack of motivation to follow through because they did not understand the value. Thinking forwards, Lourdes emphasizes the importance of engaging with community organizations to spread the word. These organizations are well rooted within their communities and are more likely to be trusted than city employees.

The DND Home Improvement Program is an income-based initiative to provide assistance with the management and financing of home improvement measures. This city service is supported through the mayor's Boston 2030 plan. Maureen Flynn, Deputy Director of the City of Boston's Boston Home Center (housed within the DND), explains that program managers' primary concern is with resolving life and safety issues such as unstable roofs, porches, railings, and dysfunctional kitchens, but they will also support energy efficiency measures as necessary. Unlike Mass Save, this program assigns a project manager to each renovation project, to assist with writing the scope of work, hiring contractors, and overseeing the implementation.

The Boston Home Improvement initiative offers several financing programs targeting 80%-135% AMI households. The primary financing mechanism is deferred 0% interest loans. Additional assistance is available to seniors with a $3,500 grant for a heating system upgrade, and a $7,500 deferred forgivable to fund lead abatement for households with a child under 6; this loan burns out after five years.

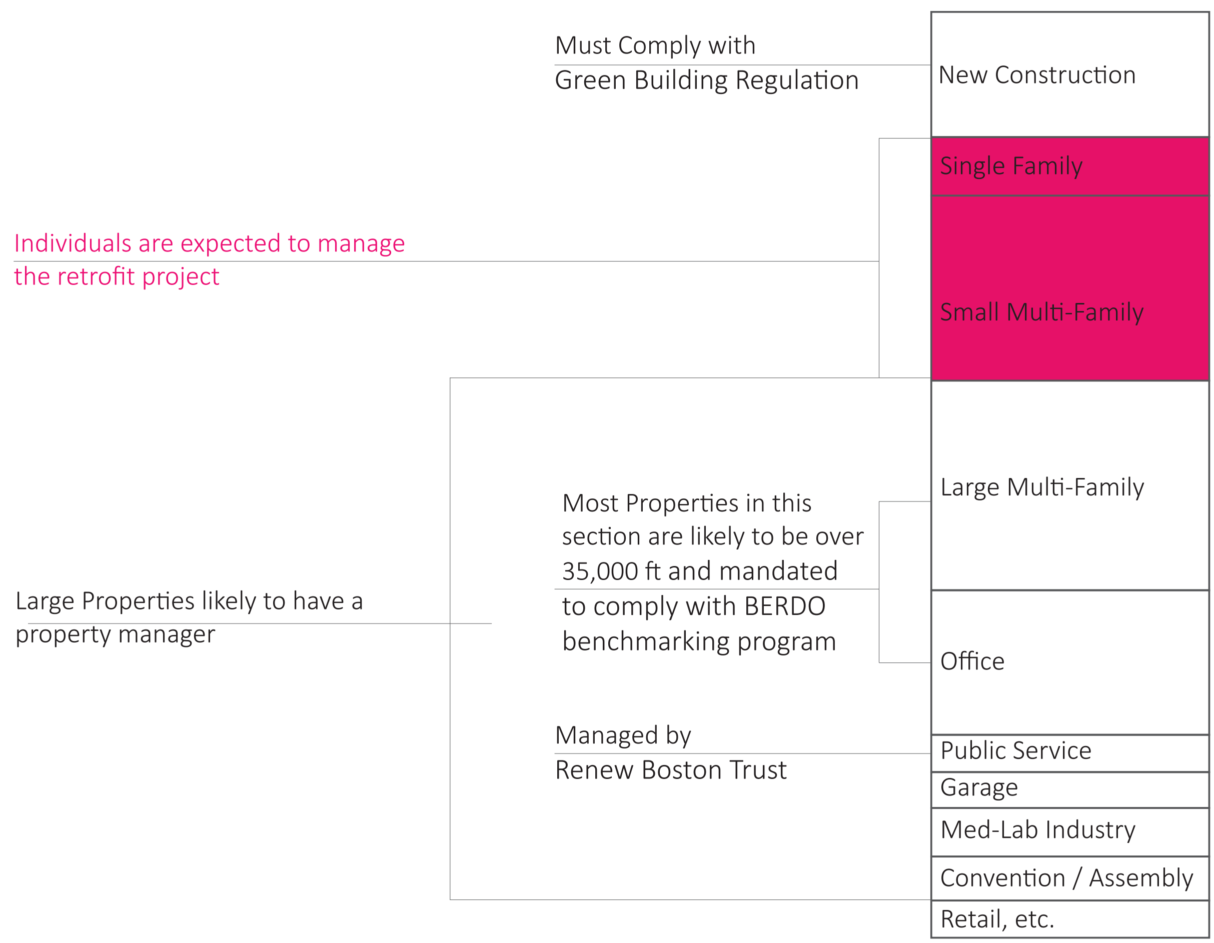
Flynn attributes the strength of this program to strong coordination between staff members. When asked about barriers to participation, Flynn outlined similar barriers to the Mass Save program such as language barriers, owner occupancy and distrust in the "system." Also, the program has only a limited amount of funds, and not everyone can participate, some households may have annual earnings over the income threshold, but may still be unable to afford renovation on their own. Looking forward, Flynn hopes to increase the loan amount to more realistically support extensive projects and to design a plan to incentivize landlords to participate.

To conclude, there is a substaintial difference between the ability of individuals to implement retrofit projects, and the ability of projects managers to do so. Figure 1 describes the estimated organizational capacity by sector, emphasizing that the small scale residential sector is the only sector where individuals are expected to be motivated, informed and capable of managing a retrofit project. Interviews show that programs for the small scale residential sectors target individuals who face many barriers to entry, among them is limited knowledge about the programs and financing options available for them, in addition to language gaps, split incentives for landlords and renters and lack of trust in government assistance.

Therefore it is not surprising that despite extensive efforts to connect Boston Citizens with Mass Save incentive programs, success has been limited. Mass Save data for 2014-2017 reveals that for this time period only 5.8% of all households received an energy audit through Mass Save, which also included implementation of simple energy conservation measures such as replacing lights to efficient LED lights and sealing drafts. Less than half the households who received an audit, continue to implement one or more energy conservation measures with Mass Save, totaling at 2.5% of all household. This data also shows that the over 90% of households that engaged with Mass Save were own-occupied.

The geography of implementation is also consistent with the City of Boston experience about the type of households who have the least barriers to entry. Figure 3 reveals that higher participation rates were documented in the more suburban parts of the city, while areas with more urban buildings types had significantly lower participation rates.

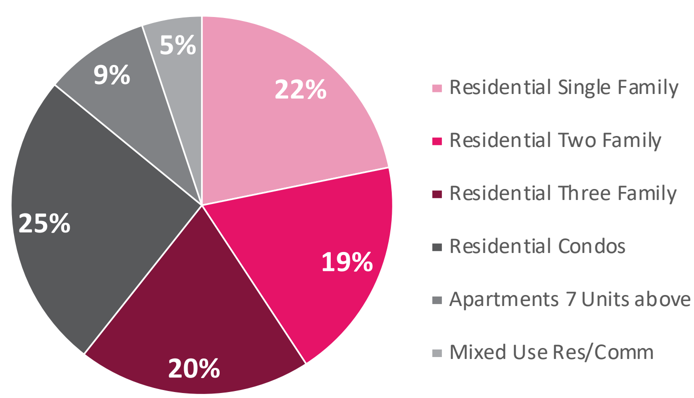
Figure 1: Estimated Organizational Capacity by Sector



Total floor area by sector adapted from Carbon Free Boston (2019)

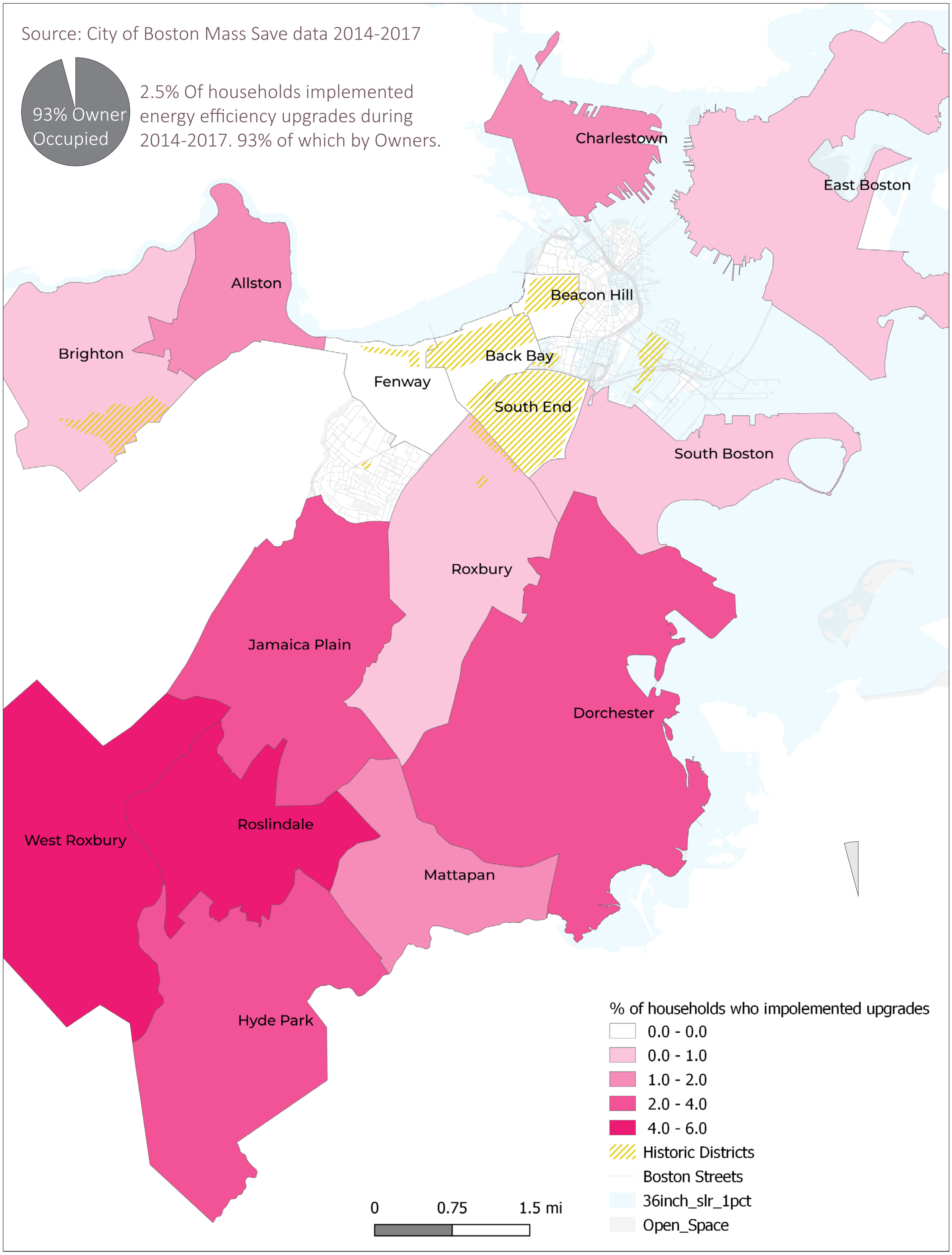
Figure 2: Total Residential Living Area by Land Use for Properties Smaller than 35000 sqft

This figure shows the distribution of residential land-uses that are not required to report their energy consumption. It shows that 1-3-unit family homes constitute 60% out of the total residential living area for properties smaller than 35,000ft.



Source: City of Boston Tax Assessor data for 2016

Figure 3: Percentage of Households that Implemented Mass Save Energy Efficiency Upgrades by Neighborhood between 2014-2017



03 Research Scope + Question + Challanges

RESEARCH SCOPE: 1-3-UNIT FAMILY HOMES

Interviews and Mass Save data reveal a knowledge gap regarding the ability of 1-3-unit family homes to engage with retrofit programs in Boston. Despite accounting for a third of the built area in the city, these buildings are too small to be required to report their energy consumption to the city's benchmarking program. Thus neither the city nor the buildings' occupants have a good understanding of their potential to reduce energy consumption. This knowledge gap is exacerbated by the lack of a property manager, that can bridge this knowledge gap for larger properties, as observed from interviews with affordable housing and public buildings property managers. Thus the scope of this research is set to 1-3-unit family homes, with the hope of bridging the knowledge gap about the incentives and barriers of the people living in these buildings to implement energy efficiency and generation measures.

RESEARCH QUESTIONS: ARE THERE SUFFICIENT INCENTIVES TO RETROFIT 1-3 FAMILY HOMES IN BOSTON?

Interviews and Mass Save data show that there is low uptake on government incentives to retrofit homes in Boston, but they do not reveal the reason for this phenomena. By examining the impact of government incentives on the ability to afford a retrofit project, this research aims to discover whether insufficient incentives explain the low uptake on government incentive programs, or whether non-financial barriers prevent people from participation. This clarification is necessary because it leads to different policy responses. The following section explains what sufficient incentives mean in the context of this research.

Sufficient incentives to retrofit a property exist when the available funding exceed the cost of retrofit implementation over a set amount of time, and there are affordable financing options that make the investment possible.

Available Funding include all revenue sources, some of them are received at the time of implementation, and some of them are incurred over time, such as energy savings due to the implementation of energy efficiency and energy generation measures. For this research, all government incentives in the form of rebates, grants, discounts, tax exemption, and tax credits, are calculated as if they were received at the time of implementation. In contrast, energy savings, which can only occur after implementation, are calculated as a revenue source that incurs over time. To account for the time value of money, revenue from energy savings is not added at its annual value, but at its discounted value over the time frame of the investment. To summarize, funding options are all the cash revenue received by the owner at the time of the investment and the present value of energy savings over time.

Financing options are financial tools that enable investment. In the context of housing retrofits in Boston, financing options are government subsidized 0% loans that provide upfront financing in place of future energy savings. Using these loans, property owners can make an upfront investment on energy efficiency measures and pay the loan over a set amount of time. This research considers these loans affordable only if the monthly return on loan is not larger than the expected monthly energy savings. Otherwise, people might make a retrofit investment that will increase their monthly expenses, and for low-medium income households, this investment will not be affordable.

The cost of the retrofit project includes the direct cost of implementing energy efficiency and energy generation measures such as insulation, window replacement, HVAC upgrade, appliances upgrade, lights upgrade, and solar panel installation, and the additional cost of overcoming barriers to implementation. These barriers are often substantial and include the cost of hazardous materials abatement, unexpected structural integrity issues, compliance with ADA, fire and safety and historic district regulation and flood proofing if the building is in a designated flood risk area.

DATA ANALYSIS CHALLENGES

Cost-benefit analysis for energy efficiency measures is a standard process that project managers apply for each building they manage to discover a bundle of energy efficiency measures that will yield a positive return on investment over a set amount of time. While this process is standard at the single building level, studying the costs and benefits of retrofit implementation for an urban area requires assumptions regarding the unique profile of buildings and users and the cost of implementation.

The unique retrofit-cost-profile of buildings is affected by the type of energy efficiency and resilience measures needed as well as measures needed to comply with regulation. Currently, there is no public data source that can provide this information at the single building level. The city of Boston tax assessor data contains parcels specific information about several attributes that are releventat to the building energy consumption profile, such as architectural typology, year built, materials, and the type of HVAC system. But this data set is incomplete and doesn't account for all the information needed. Other public data sets such as the historic distric overlay and flood risk overlay reveal information that is relevant to the cost of retrofit implementation, but without details about how individual buildings will be affected. Therefore, there are data analysis challenges for determining the variables that affect the energy profile of buildings and the cost of implementation.

The unique profile of users affects the pattern of energy consumption as well as the ability to access government funds. For example, annual energy consumption for the same house can significantly vary if the people using it are heavy consumers that leave the lights and heating on all the time or light consumers that scarcely use appliances and heating. Also, since government benefits are allocated by need, some users may be eligible for substantial financial assistance, while others will only be eligible for minimal assistance. Due to privacy concerns, there are no public data sets that place specific users in buildings. Instead, demographic information is provided at a scale of an urban block, which can include tens to hundreds of buildings. Consequently, there is a data analysis challenge for determining the user profile at the individual building level.

Lastly, the cost of implementation is negotiable and varies by the constructor, location, and building specific challenges. Data about the price of implementing different energy efficiency and generation measures is often given as a range of prices. Furthermore, the real value of unexpected renovation costs can only be discovered at the time of implementation. Therefore, uncertainties about the range of costs and the type of work needed impact the ability to predict the total cost of a retrofit project.

To conclude, several data analysis challenges affect the ability to create a building-specific user and energy profile and accurately assess the costs and benefits of retrofit projects at an urban scale. Primary challenges include discrepancy between data types, incomplete data sets, construction prices uncertainties, and the necessity to protect citizens privacy by not disclosing personal information at the individual building level. Thus, the mission of creating a retrofit cost-benefit analysis for an urban region will require making educated assumptions about the missing variables.

04 Methodology

To Assess the Current State of Retrofits in Boston

This chapter describes a multi-step process to create, analyze, and visualize a retrofit data set for 1-3-unit family homes in Boston. The methodology builds on previous Urban Building Energy Modeling (UBEM) research conducted at the MIT Sustainable Design Lab (SD) and complements this work by examining the impact of energy savings and government incentives on the financial feasibility of retrofit implementation. The first part of this chapter introduces the UBEM framework, the second part provides a methodology overview, and the third and last part describes the step by step methodology application to two use cases.

UBEM INTRODUCTION

The foundation for this analysis is the Urban Building Energy Model methodology developed by Reinhart and Cerezo Davila (2016) as a bridge between the detailed building scale energy model and estimated regional scale energy model.[33] The UBEM workflow was developed to address the increasing demand for decision-making tools that can predict the "future effects of comprehensive energy retrofitting programs and energy supply infrastructure changes" at the neighborhood to urban scale. Its strength is in the ability to use multiple public data sets to create UBEM from aggregated individual building energy simulations.

The UBEM methodology addresses key data analysis challenges with regards to buildings' energy profiles. It uses a combination of expert knowledge and public datasets to create a location-specific building energy profile, that responds to weather data, building archetype, materials, systems, and area. This tool is designed to estimate the total neighborhood energy consumption for different energy conservation scenarios, and should not be used to gather insights about individual buildings. Further development of the UBEM methodology by researchers at the MIT SD Lab addresses data analysis challenges with regards to user profiles. Bemis[34] and Irani[35] , developed a UBEM for Dudley Triangle and Boston South End, that includes user classification to predict the impact of user behavior on the total neighborhood energy consumption. They defined four distinct user group and created a unique user adnbuilding specific energy consumption profile. Using census data, they identified the distribution of users across the neighborhood and used weighed averages to estimate the total neighborhood energy profile. The novelty in their research was in producing a UBEM that is responsive to user behavior.

UBEM methodology provides an answer to the question of what change is needed to transition to low carbon buildings. By doing so, it creates a building and user-specific energy profile, which describes both the current energy consumption and the potential for reduction in energy consumption under different energy conservation measures scenarios. Since government incentives are also allocated by a unique user and building profiles, these classifications enable the current research into the costs and benefits of retrofit implementation. This thesis uses UBEM methodology as a foundation and adds a new workflow to answer the question of whether the current incentive programs are sufficient to implement the suggested energy efficiency and generation measures.

METHODOLOGY OVERVIEW

Since the workflow to assess the feasibility of retrofit implementation is dependent on UBEM outputs, this section will provide an overview for both the UBEM methodology steps and this thesis's methodology steps, highlighting key variables that connect the two workflows. For the full list of data sources used in this analysis, see Appendix A.

First, Figure 4 describes the MIT SD Lab UBEM methodology steps, adapted from Jamie Bemis's thesis paper, developed in collaboration with Ali Irani under Christoph Reinhart's supervision (2016). This methodology creates a parcel and user-specific energy profile and then correlates the result to neighborhood demographics to estimate the total neighborhood energy consumption for different Energy Conservation Measures (ECM).

The first step is to develop a baseline energy model using buildings' geometry, weather data, and the classification of building archetypes by construction type and energy loads. This step also includes the creation of an energy consumption profile for four user types: families, elderly, young professionals, and students. Families are classified as four-member households with medium appliance density and the highest equipment loads. Elderly couples are classified as two-member households with less efficient appliances, but lower equipment density. Young professionals are classified as three-member households with high density occupancy, and students are classified as four-member households with the highest density occupancy. At the end of this step, four energy models have been built for each building, one for each user type.

The second step defines two ECM scenarios and quantifies the impact of the ECMs on the baseline model. Energy Conservation Measure 1 (ECM1) includes easy-to install Improvements such as weatherization and lights upgrade to LED. These measure are currently provided at no cost through a Mass Save energy audit. Energy Conservation Measure 2 (ECM2) requires a substantial building renovation including insulation of attic, basement and walls, window upgrades, HVAC system upgrade and appliances upgrade to energy star or better. This scenario also includes the installation of solar panels. Primary incentives to support this investment are detailed in figure 7. At the end of this step, each building was assigned three energy consumption profiles: a baseline to account for the current energy consumption, ECM1 to account for easy to implement measures, and ECM2 to account for a deep energy retrofit.

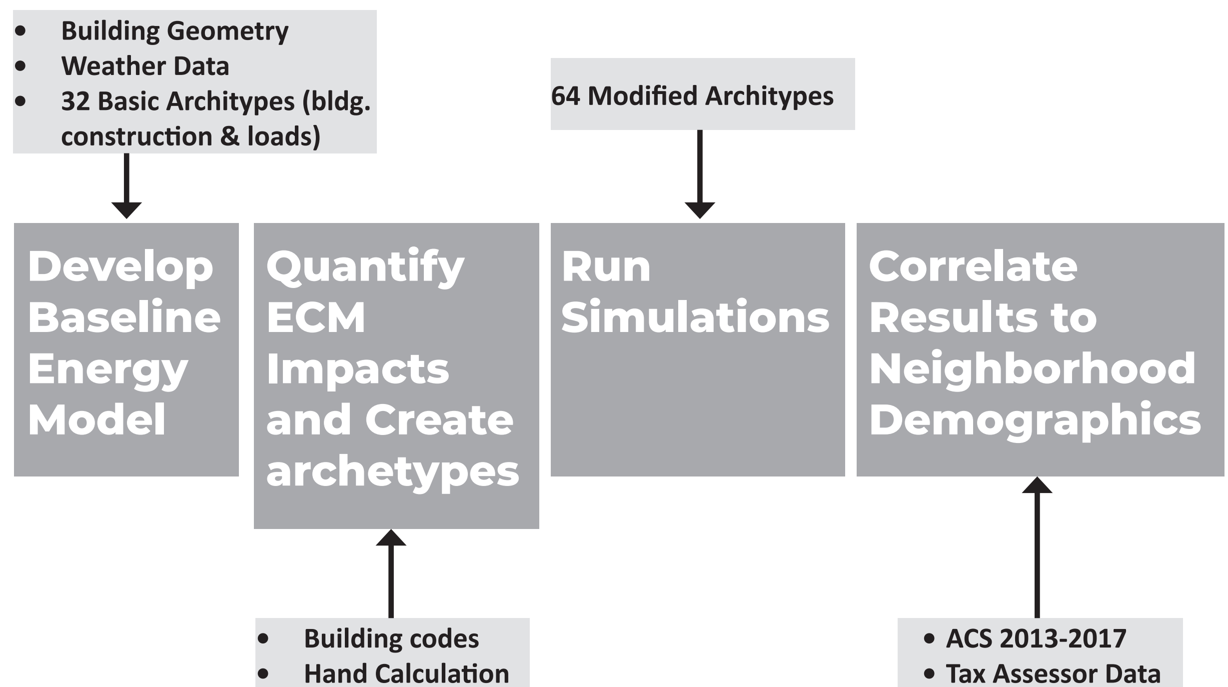
During the third step, energy simulations are run to calculate buildings' energy consumption for the baseline model and the two ECM scenarios. This step ends with a total of twelve energy simulations for each building, which reflect four energy simulation results for each of the three ECM scenarios, one for every user type.

Lastly, the fourth step utilizes tax assessor data and census data to correlate the results to the neighborhood demographics. This final step produces the total neighborhood energy consumption for each ECM, which reflects the neighborhood unique building types and demographic profile.

Using similar methodology to estimate neighborhood scale results from the aggregated results of individual buildings, figure 5 describes a new workflow to assess the impact of retrofit affordability on the potential to reduce the total neighborhood energy consumption. This workflow extends the user-building-energy profiles that were developed in the previous research, to incorporate the costs and benefits of retrofit implementation. Afterward, it uses a similar process to correlates the result to neighborhood demographics.

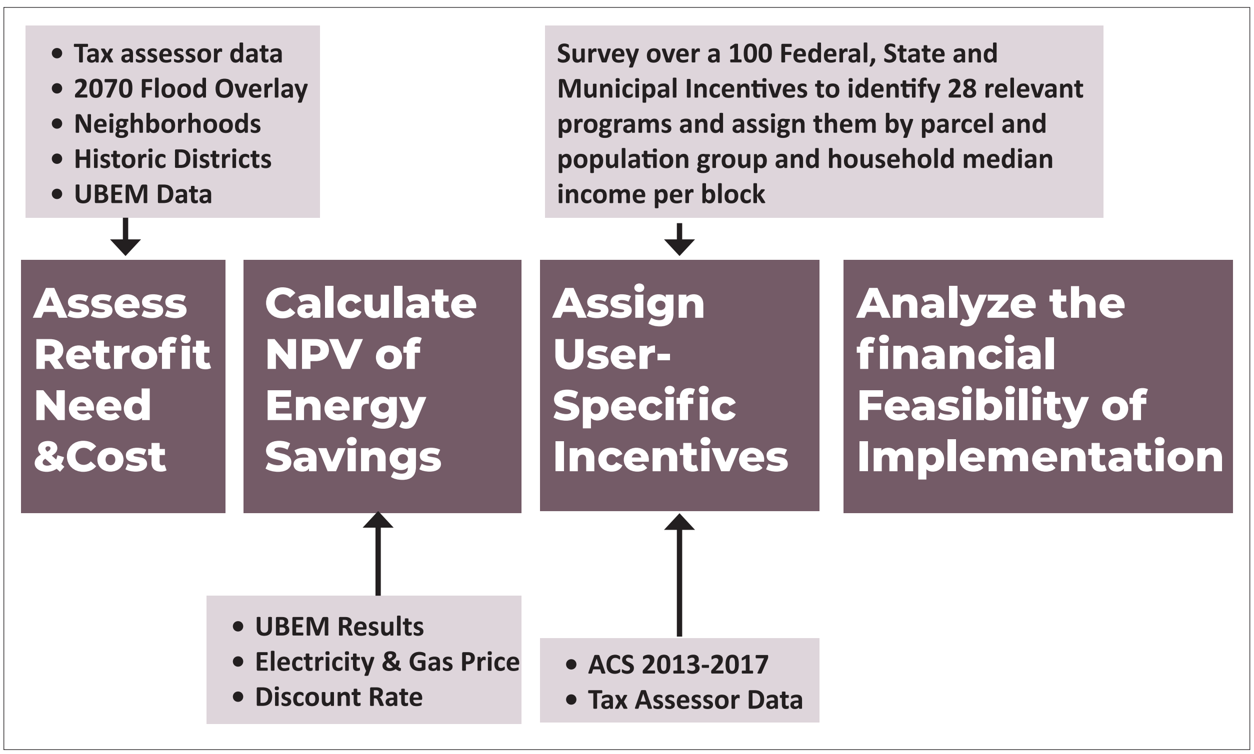
This workflow begins with assessing retrofit necessity and cost by parcel. Public records and tax assessor data are used to determine retrofit

Figure 4: MIT Sustainability Design Lab UBEM Methodology Steps



Adapted from "UBEM as a Dynamic Tool For Sustainability Planning", Jamie Bemis and Christoph Reinhart (2016)

Figure 5: Cost Benefit Analysis Methodology Steps



necessity. Next, the combination of tax assessor data, Boston Historic Districts maps, and Boston flood projection map are used to estimate which buildings will need to overcome barriers to implementation. Lastly, cost is assigned to each of the energy conservation measures identified in the previous research. At the end of this step, each building is assigned a total retrofit cost, which includes the cost to overcome barriers (where needed) and the cost of energy efficiency and generation measures.

The second step is to Calculate the Net Present Value (NPV) of Energy Savings over a set amount of time. Annual energy savings for each user type were calculated using the results of the UBEM simulations as an input, and the 2018 price for electricity and gas. Next, to account for the time value of money, the NPV of energy savings is calculated for a set amount of time, using a constant discount rate. Since this research is concerned with deep energy retrofits, the NPV of energy savings was calculated only for ECM2, which accounts for the deep retrofit scenario. At the end of this step, each building is assigned four energy savings NPVs, one for each user type.

The third step identifies federal, state, and municipal incentives available for 1-3-unit family homes in Boston and determines the eligibility to receive government benefits for each user-building profile. Government incentives are assigned by building type, location, household income, household size, and householder age. Appendix A contains a government incentives allocation tree, and Appendix B includes the full list of incentive programs accounted for in this model. This step results in four benefit profiles for each building, one for each user group.

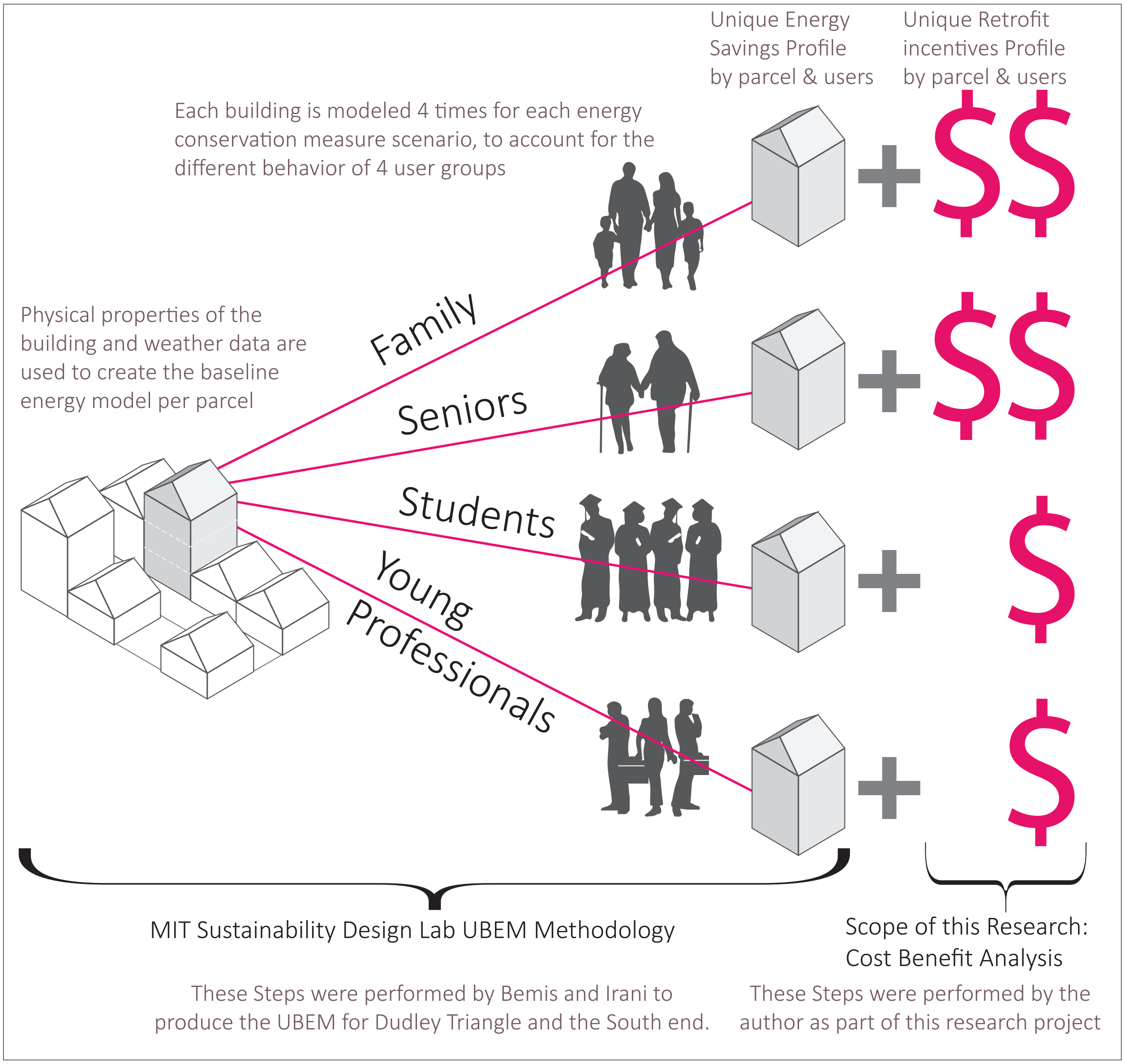
To summarize, step one estimates retrofit costs, step two estimates the value of energy savings over time, and step three estimates the value of applicable government benefits. Put together, these are the components of the cost-benefit analysis administered in this study.

The fourth and last step computes the results of previous steps to produce a cost-benefit analysis. Since each building is modeled once for each user type, this step results in a user-building-specific cost-benefit analysis. A retrofit project is financially feasible if the benefits from government incentives and energy savings outweigh the total retrofit cost. Since energy savings incur over time, financial feasibility is tested for different time periods, to better understand the impact of longer payback periods on the ability to afford a project. Lastly, tax assessor data and census data are used to correlate the results to the neighborhood demographics.

The final product of this workflow compares the total neighborhood energy expenses for five scenarios. The baseline scenario describes the current conditions, ECM1 describes the impact of mandating a Mass Save audit for all buildings, ECM2 describes the impact of mandatory deep retrofit implementation for all buildings. And ECM2-Afford describes the impact of retrofit implementation only by households that have sufficient incentives to retrofit.

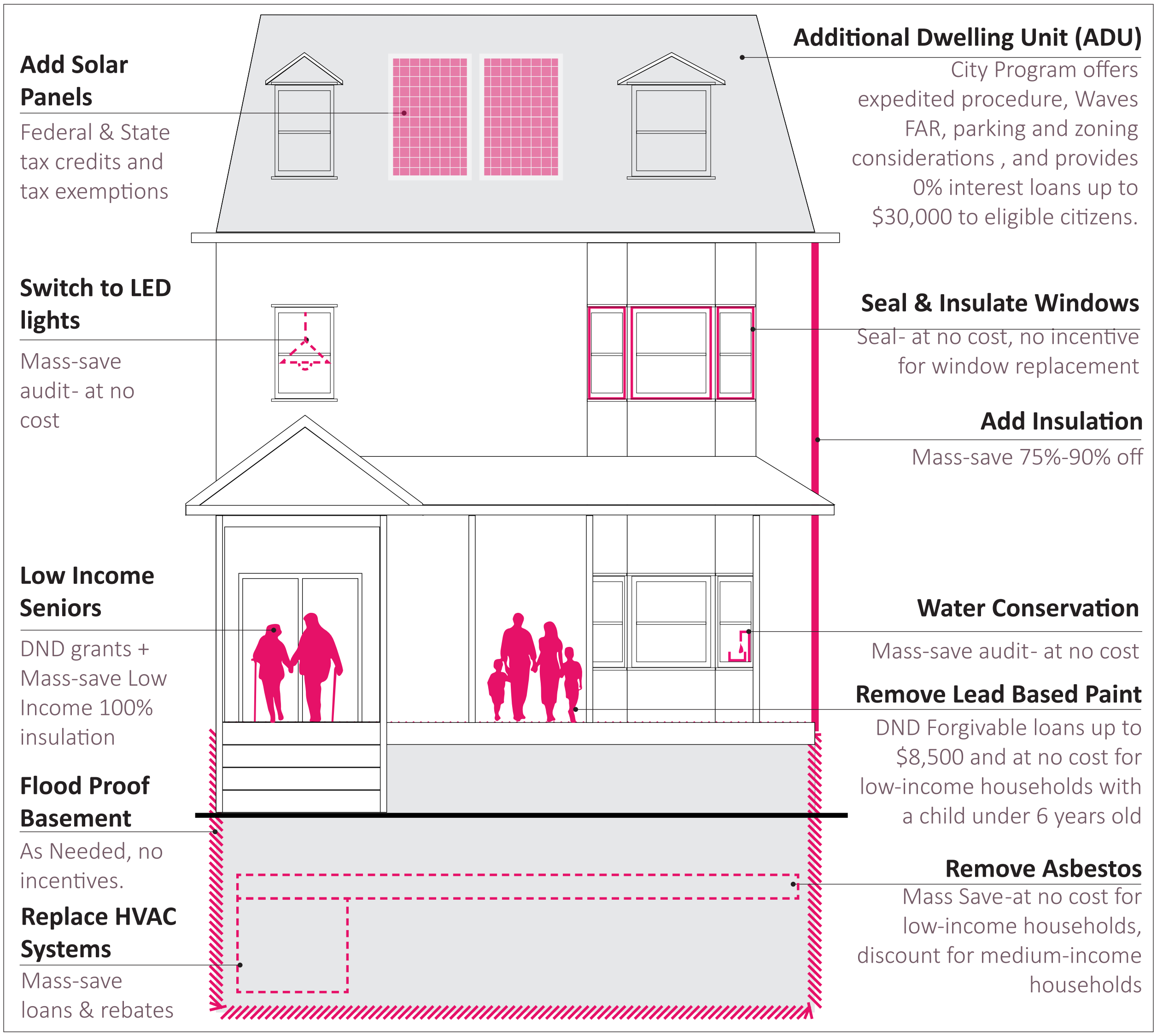
To conclude, UBEM methodology assesses the current energy consumption of each building, recommends applicable energy conservation measures, and calculates the potential energy savings if those measures are implemented. Recognizing that different users have different energy consumption patterns, each building is modeled four times to account for four user types. This thesis uses the UBEM results as inputs, and assigns each building a retrofit cost based on the recommended energy conservation measures and the barrier mitigation costs. In addition, each user is assigned a benefit profile unique to users' energy consumption pattern and eligibility to government incentives. Finally, a cost-benefit analysis is conducted for each user type, and retrofit is determined affordable the benefits outweigh the costs. Results are correlated to neighborhood demographics to estimate the percentage of households that can afford a retrofit at the neighborhood scale.

Figure 6: Illustrative Methodology Diagram



The synergies between the two workflows are described in figure 6, which emphasizes the role of user classification as the connecting tissue between energy efficiency analysis and cost-benefit analysis. While the cost of retrofit implementation is identical for all users, the benefits vary depending on energy savings and eligibility to government incentives, resulting in a user-building specific benefit profile.
Since demographic information is not available at the single building level, incentives are assigned to predefined user-types derived from the existing UBEM model. These user-types are not comprehensive of all household types in the studied neighborhoods, but they are representative of common household types
Primary need-based government incentives are provided for income-eligible households with additional aid for households with people over 60 or under 6, which further differentiates the benefit profile of each user type.

Figure 7: Primary Federal, State and Municipal Incentives to Support Energy Conservation and Generation Measures for 1-3-Unit Boston Homes



There are 128 federal and state energy efficiency incentives program applicable in MA, out of which 60 target residential properties and 28 are applicable in Boston. In addition to those, the City of Boston offers several need-based incentive programs. Each of these programs has different eligibility and income criteria and different application processes. Figure 7 describes typical retrofit measures for 1-3-unit family homes in Boston and the primary federal, state, and municipal incentives to support implementation. The federal and state governments provide tax credits and exemptions for solar energy. The state government, through Mass Save provides an umbrella of energy efficiency programs to upgrade lights, appliances, and HVAC equipment, as well as to install insulation. Income eligible citizens are provided with further financial assistance for hazard mitigation and retrofit implementation. Lastly, the City of Boston offers several incentives for income-eligible citizens, with additional assistance for senior households or households with a child under 6. As of May 2019, there are no incentives to implement resilience measures such as flood proofing. The full list of incentives used in this model is detailed in Appendix B.

STEP BY STEP METHODOLOGY APPLICATION TO USE CASES

The following section introduces Dudley Triangle and the South End as the use cases and describes the step by step process to produce the final data analysis and visualization for each neighborhood. Each step is discussed in detail and the interim data analysis results are visualized and explained for each of the use cases. Since this thesis adds a new workflow to the existing UBEM developed by Bemis, Irani, and Reinhart (2016), the selection of use cases is also derived from the previous research. That said, differences in neighborhood demographics, building typologies, regulation, and exposure to climate risks, make these use cases ideal for exploring how these variables affect the financial ability to retrofit housing.

USE CASES INTRODUCTION

Figure 8 shows the location of the use cases with regards to the spatial distribution of 1-3-unit housing in Boston and their exposure to cost prohibitive historic district regulation and flood risks. Within this context, it is easy to see the overwhelming differences between the two use cases. The South End is an urban neighborhood, located in proximity to Boston's Central Business District. All of the buildings in this area are part of the Boston Historic district zoning overlay, which requires a longer review process and mandates strict standards for persevering the exterior of the building. The South End is also a coastal neighborhood, with high exposure to future flood risks due to extreme weather events and sea level rise. In contrast, the Dudley Triangle area is part of the residential inland neighborhood Roxbury and isn't exposed to coastal flood risks. Its residential typologies are similar to other residential neighborhoods across the city.

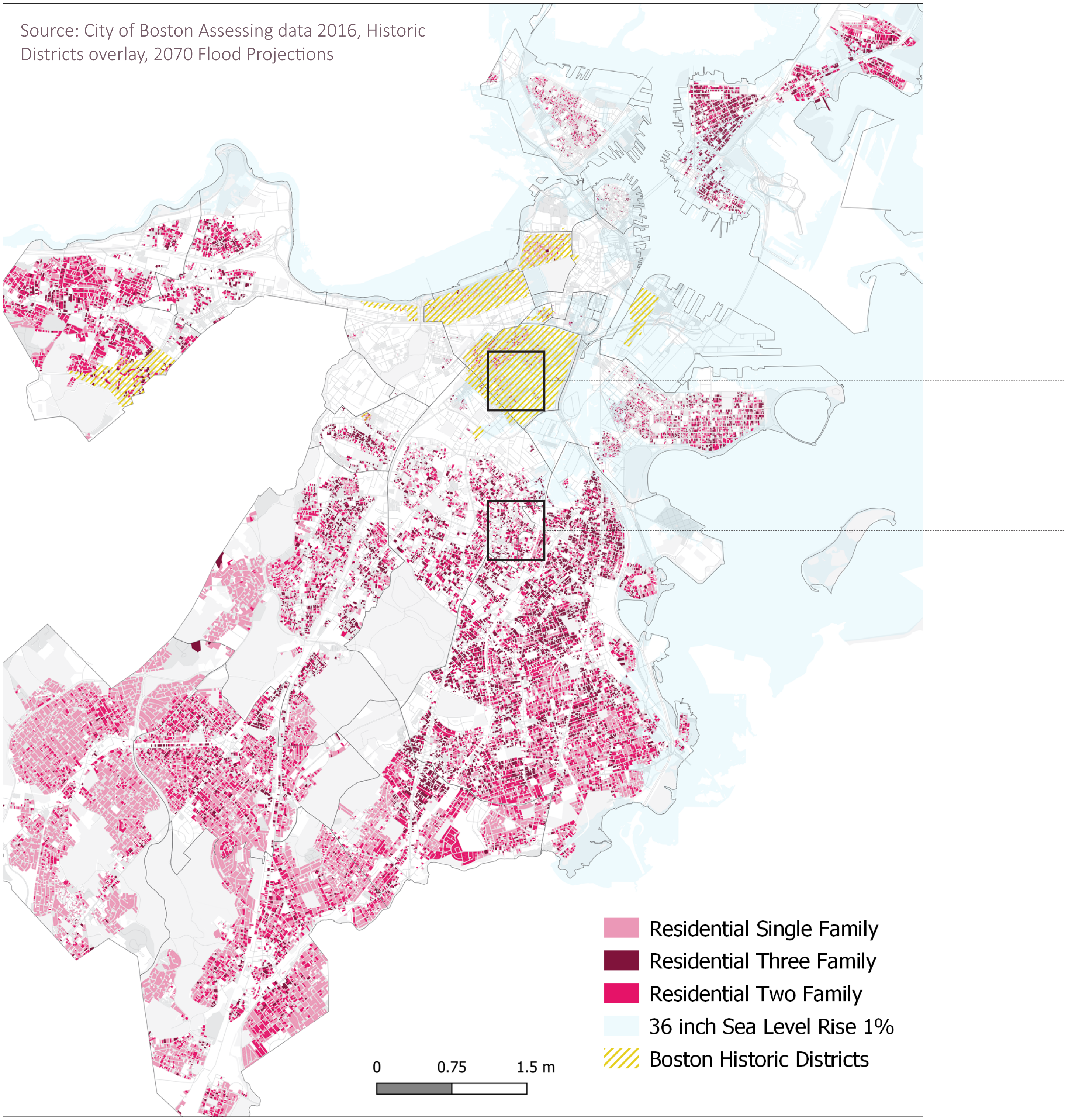
Figures 9-10 provide a closer look at the land use distribution for the two neighborhoods. There are 506 single-family, two-family and three-family homes in the South End, which amount to 38% of the residential parcels in this area. The Dudley triangle area includes 360 single-family, two-family, and three-family homes, which amount to 85% of the residential parcels in this area. Land-use information is derived from the 2016 City of Boston tax assessor data.

Figures 11-12 show the median household income for both neighborhoods, distinguishing between the high-income households in the South end, and the lower income households in Dudley Triangle. One exception is an affordable housing project located at the center of the south ends. Since need-based government assistance is substaintial, available funding for retrofit measures will reflect the difference in income levels. Demographic information is derived from the 2013-2017 American Community Survey Census.

Figures 13-14 show the ownership status in both neighborhoods. It is interesting to observe that both neighborhoods have a high percentage of owner-occupied housing. Nearly 80% of South End buildings and 70% of Dudley Triangle buildings are owner-occupied. Ownership is important because it determines the ability to engage with Government programs and implement renovations. Ownership information is derived from the 2016 City of Boston tax assessor data.

Lastly, Figures 15-16 are for illustrative purposes and describe the street-scape of the neighborhoods. While the South End is known as a vibrant urban neighborhood, the Dudley area is known for its strong community leadership. Buildings in this area are part of a community land trust. The Dudley Street Neighborhood Initiative (DSNI) manages development in this area for the benefits of its residents and in accordance with its neighborhood revitalization plan. It is a strong organization that has the organizational capacity to engage with retrofit programs at the neighborhood scale.

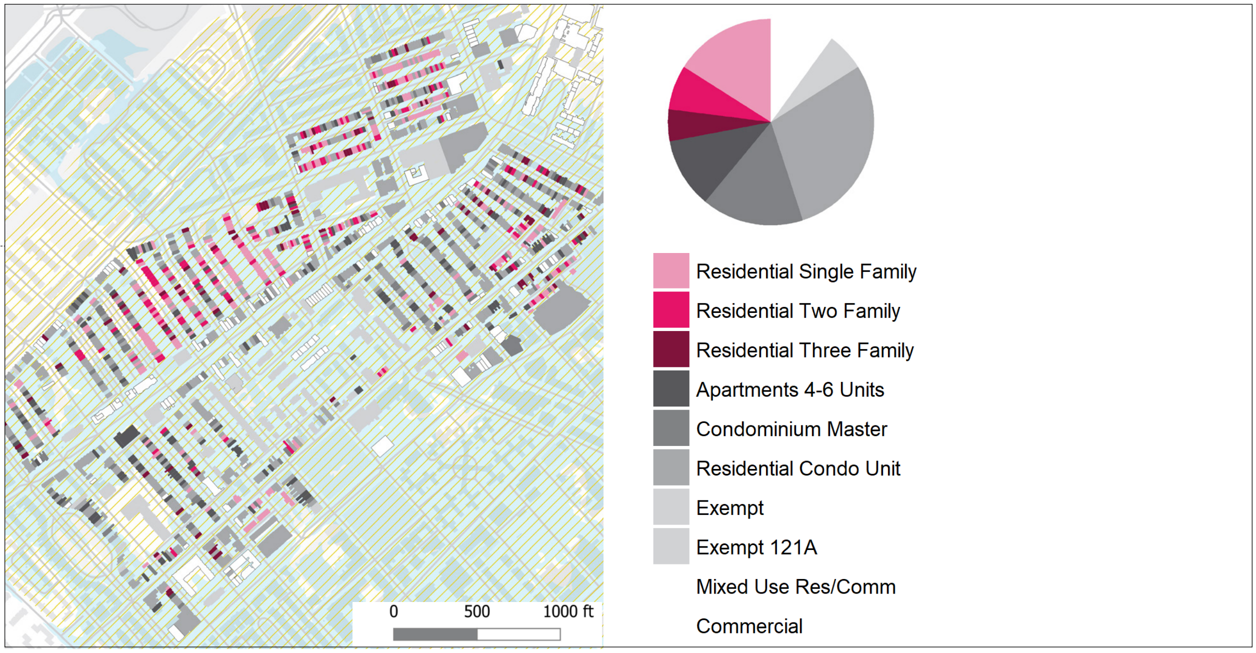
Figure 8: 1-3-Unit Family homes in Boston



1-3-unit family homes in Boston are mostly located outside of the Central Business District, with housing density declining towards the city edges.

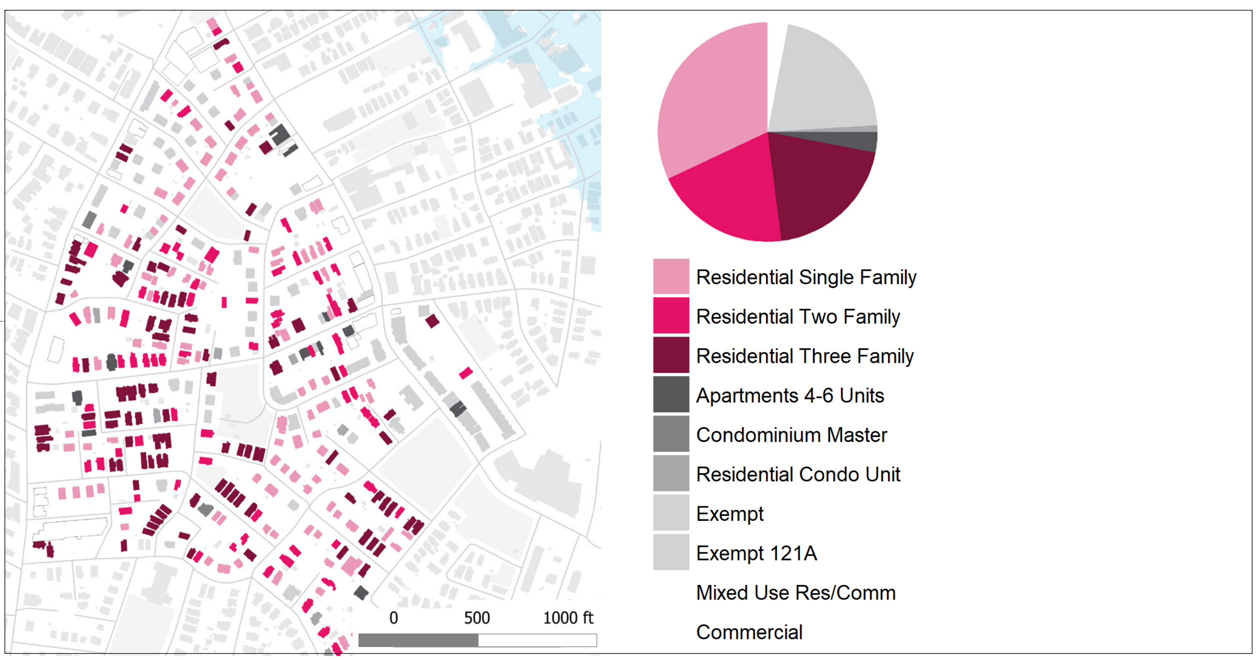
1-3-unit family homes in coastal neighborhoods may be exposed to flood risks due to sea level rise and extreme weather events.

Figure 9: South End - Land Use



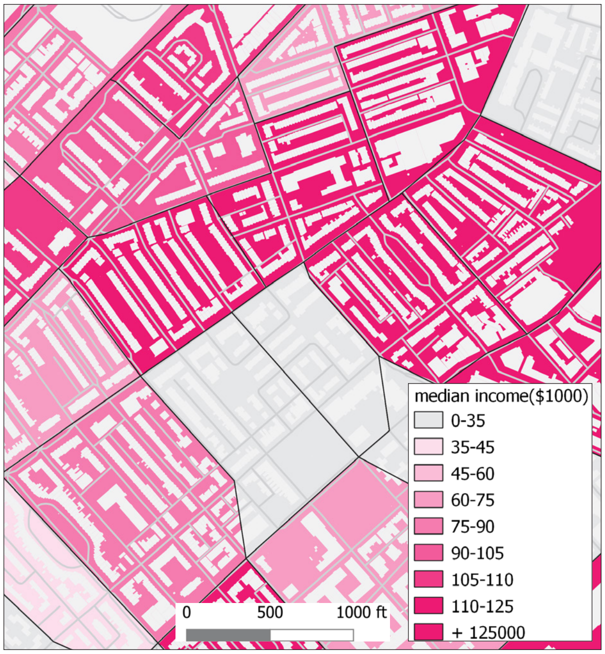
A third of the housing units in the South End are 1-3-unit family homes. Like most buildings in this area, these houses are located within the South End Historic District and must comply with Historic District regulation. These houses are also under flood risk.

Figure 10: Dudley Triangle - Land Use



The majority of housing units in the Dudley Triangle are 1-3-unit family homes, with relatively even distribution between single family homes and small multi-family homes. Buildings in this area are not under flood risks or part of a historic district.

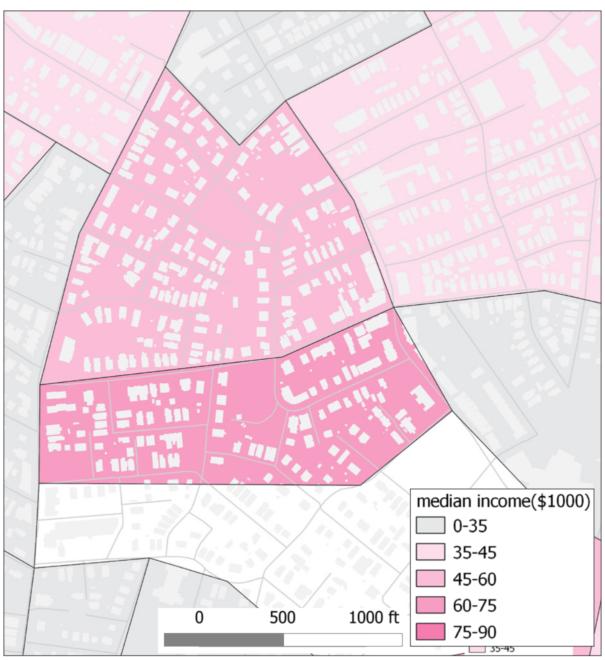
Figure 11: South End Median income



Source: American Community Survey Census 2013-2017

South End households are medium to high income. Except for one affordable housing project.

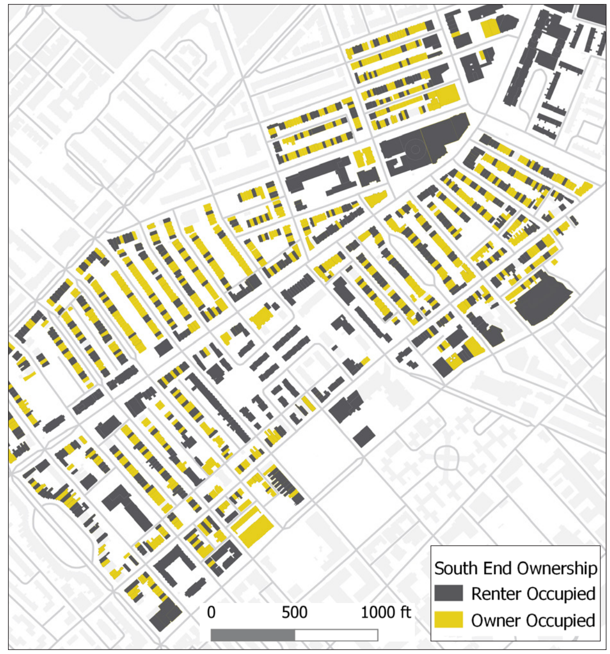
Figure 12: Dudley Triangle Median income



Source: American Community Survey Census 2013-2017

Dudley Triangle households are low-medium income.

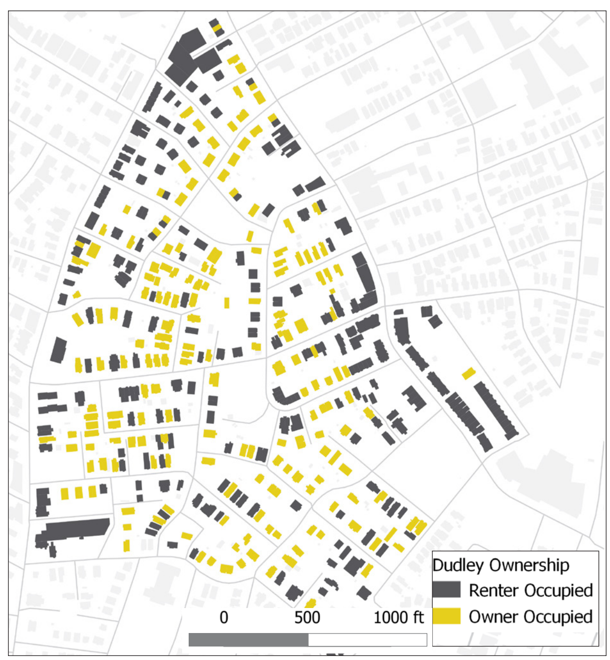
Figure 13: South End Home Ownership



Source: City of Boston Tax Assessor Data 2016

Nearly 80% of single-family and small multi-family homes in the South End are owner occupied.

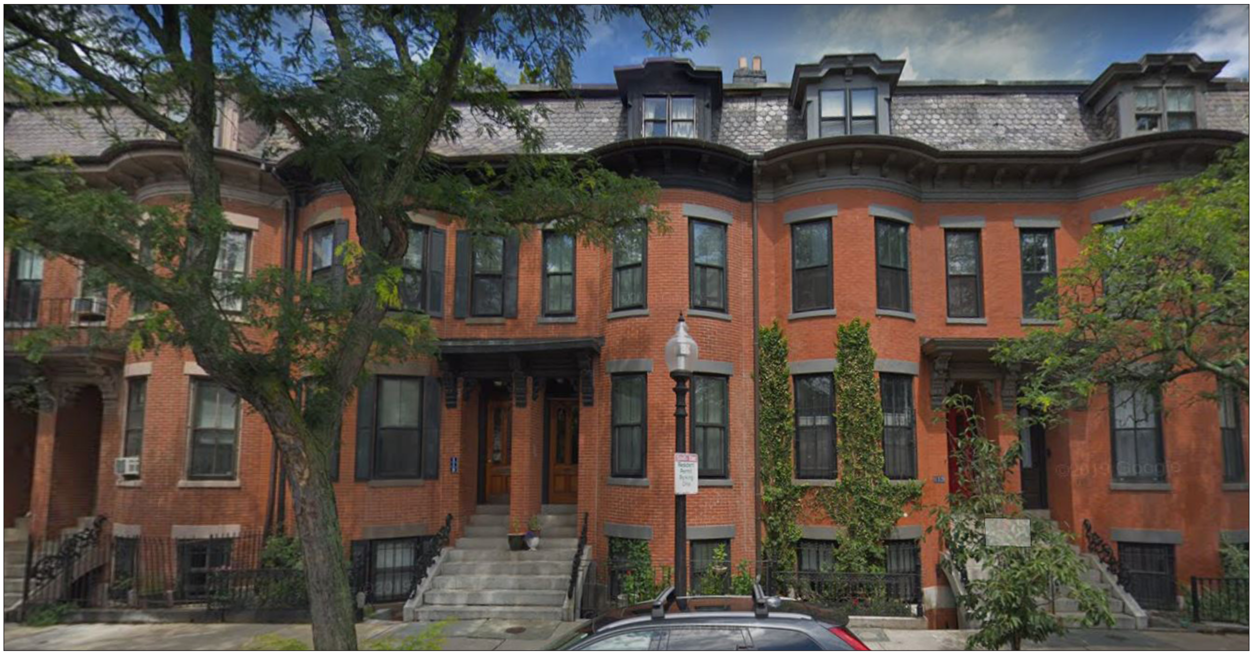
Figure 14: Dudley Triangle Home Ownership



Source: City of Boston Tax Assessor Data 2016

Nearly 70% of single-family and small multi-family homes in Dudley Triangle are owner occupied.

Figure 15: South End



Source: Google Street View

South End historic buildings are easily recognizable by the red bricks and large windows. They also typically have a story below street level, which indicates the previous entry level of the buildings.

Figure 16: Dudley Triangle

Source: Google Street View

At the front is a community Garden in Dudley Triangle which demonstrates the community's organizational capacity. At the back are Common building types in Dudley Triangle.

STEP 1: ASSESS RETROFIT NECESSITY AND COST

The first step evaluates each parcel for retrofit necessity and cost, depending on the building's location and the year it was built or remodeled. Both variables are derived from the City of Boston Tax Assessor data for 2016.

Following insights from interviews and policy review, every building that was built or remodeled before the Boston green energy standards were enacted in 2007[36], is classified as in need of retrofit. The reason for this assumption is that the quality of design, construction and insulation might be poor in houses that did not have to comply with green energy standards. In addition, over 10 years have passed since 2007, and even for relatively news homes, equipment and appliances might be in need of repair.

Next, a review of public records reveals which buildings are likely to have barriers to implementation. For the purposes of this research, barriers to implementation are any additional costs that are needed during the renovation process either to abate hazardous materials or to overcome structural risks. Depending on a buildings age, the following barriers might by encountered:

Irregular Construction can be expected in buildings built between 1950-1985.

Asbestos siding or insulation were very common building materials between 1800-1980. In the later 1970's, the Environmental Protection Agency (EPA) enacted several regulations to ban the use of some asbestos containing materials, and by 1989 it banned the use of most asbestos containing material.[37]

Vermiculite Insulation is likely to contain asbestos. According to the EPA, over 70% of vermiculate sold in the U.S from 1919-1990 is contaminated with asbestos.[38]

Lead Paint may be found in any building constructed prior to 1978.[39]

'Knob and Tube' electrical wiring was a common method for wiring electricity up until the 1940's. This system has no ground wire, and due to age, it's casing may be broken and might be a fire hazard.

While there is no building specific record to identify which of the following barriers might apply, interviews revealed that asbestos and lead abatement are the most common hazards in the Boston area. To account for the cost of barrier abatement, any building built or remodeled before 1985 is considered to have a barrier to retrofit implementation, and is assigned a barrier mitigation cost relative to the total building area.

Lastly, each Energy Conservation Measure (ECM) recommended by previous UBEM research ECM2 scenario, is assigned a building-specific cost based on the total living area of the building, its estimated window area, its perimeter and its available roof area for solar installation. The model assumes that building owners will also want to upgrade the following equipment to energy star or better appliances: refrigerator, washing machine, dryer, dishwasher, and oven. In addition, any building that is part of a historic district is assigned a cost premium for insulation and window replacement, to account for the additional cost required to comply with regulation. Another additional cost is assigned to any building located in a flood risk overlay, to account for the cost of flood proofing. The full list of cost estimates is described in Appendix D. The sum of all resiliency, regulation compliance, energy efficiency and generation costs is titled retrofit cost.

At the end of this step, buildings that do not need to be retrofitted are filtered out. The remaining buildings are assigned a total cost which is the sum of the retrofit cost and the barrier mitigation cost.

Figure 17: South End Retrofit Neccesity and Cost

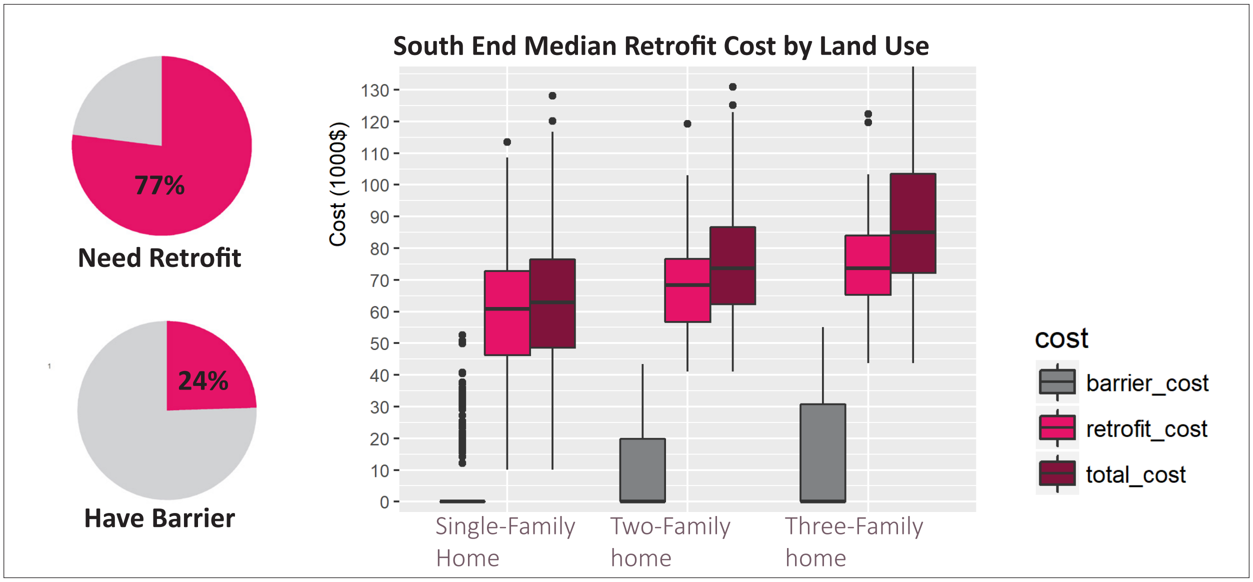


Figure 17 shows that 77% of 1-3-unit family homes in the South End will benefit from a retrofit project. Also, 24% of 1-3-unit family homes are likely to have a barrier to implementation. The box-plots represent the range of costs for each land use type and cost type. It shows that single-family homes are less affected by barriers than 2-3 family homes. It also shows that costs increase moderately with building size.

Figure 18: Dudley Triangle Retrofit Neccesity and Cost

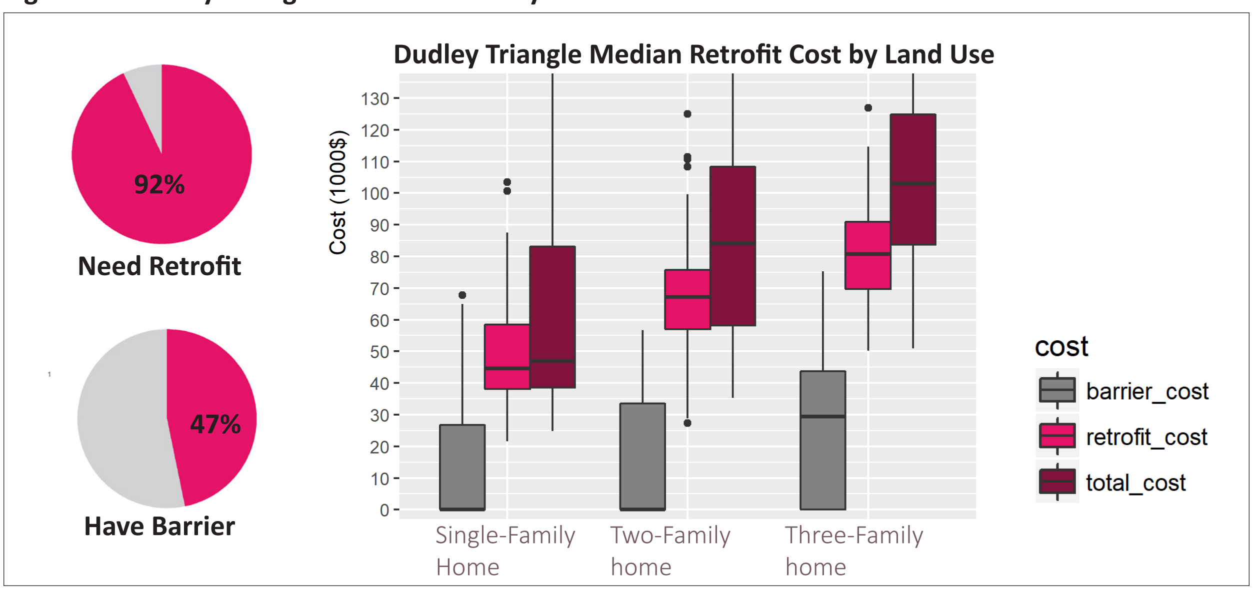


Figure 18 shows that 92% of 1-3-unit family homes in Dudley Triangle will benefit from a retrofit project. Almost half of these homes are likely to have a barrier to implementation. The box-plots represent the range of costs for each land use type and cost type. It shows that single-family homes are less affected by barriers than 2-3 family homes. It also shows that costs increase with building size. The wide range of total costs responds to the wide range of mitigation costs.

STEP 2: CALCULATE THE NET PRESENT VALUE (NPV) OF ENERGY SAVINGS

This step utilizes results from the existing UBEM to estimate the user-building-specific annual energy savings and their net present value over a set amount of time. As a reminder, for each ECM scenario, each building was modeled four times, once for each user, to account for different consumption patterns. For this reason, the boxplots show four users for each land use, revealing user-induced differences for the same housing stock.

To understand the monetary value of each ECM, UBEM simulations results needed to be converted from Energy Use Intensity (EUI) units to dollar expenses. According to a report on the average energy prices in Boston-Cambridge-Newton for 2018, the average electricity price was $0.225 for KWh, and the average gas price was $0.05 for kwh. These costs were used to calculate the annual energy expenses for the baseline model and the two energy conservation measure scenarios. Figures 19-20 show that for both neighborhoods, ECM1 scenario can reduce annual energy expenses by 10% on average, and ECM2 can reduce annual energy expenses by 50% on average.

Next, the Net Present Value (NPV) of energy savings was calculated for four periods: 3 years, 5 years, 7 years, and 10 years, using an 8% discount rate. This discount rate is set to be above the inflation rate, but still low relative to real-estate investments because it is intended to reflect the risk associated with the investment, and not a desirable profit rate. While energy savings from energy efficiency and generation measures are certain, the extent of the savings is uncertain. The monetary value of energy savings is also uncertain and depends on energy price, and user behavior after the retrofit project has been implemented.

At the end of this step, each parcel is assigned a user-specific energy savings NPV for each period. Figures 21-22 show the results for the 10-year time period. The boxplots are organized by land use, when each land use is modeled 4 times, once for each user type. Variation between boxplots of the same land use reflects only the difference between the energy consumption pattern of users. Variations between land use type reflect variation in building area and architectural typology.

Figures 19-20 show that the potential for annual energy savings for 1-3-unit family homes in Dudley Triangle is slightly higher than the potential for annual energy savings in the South End. This difference is probably caused by the fact the Dudley homes are slightly larger than South End homes, and thus consume more energy. These figures also show that there is more considerable uncertainty with predicting energy savings in the Dudley area, than in the South End. This uncertainty is commensurate with the greater diversity of architectural typologies for 1-3-unit family homes in Dudley, in comparison with the South End.

Finally, figures 21-22 show that while annual energy expenses differ significantly by user, the compounded value of energy savings over time is similar across all users within the same land use category.

Figure 19: South End Median Annual Energy Expenses by ECM ($1000)

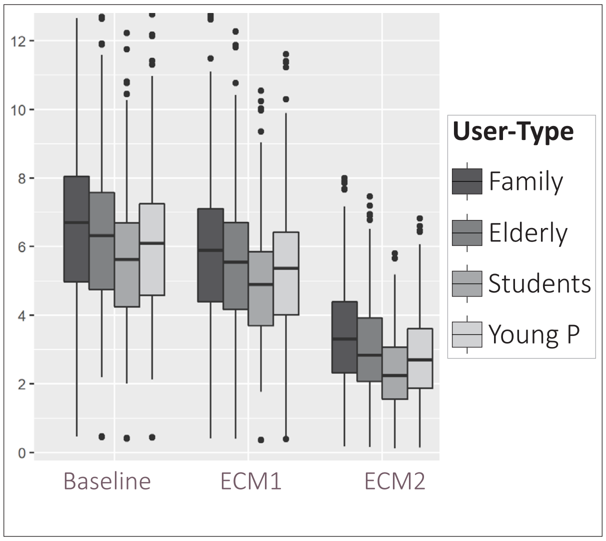


Figure 19 shows the range of annual energy expenses for 1-3-unit family homes in the South End for the baseline and the two ECMs. On average, ECM1 reduces neighborhood-wide energy expenses by10% and ECM2 by 50%.

Figure 20: Dudley Triangle Median Annual Energy Expenses by ECM ($1000)

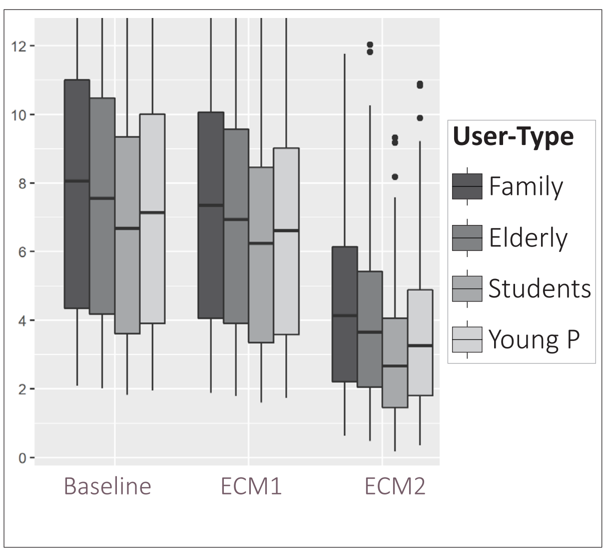


Figure 20 shows the range of annual energy expenses for 1-3-unit family homes in Dudley Triange for the baseline and the two ECMs. On average, ECM1 reduces neighborhood-wide energy expenses by10% and ECM2 by 50%.

Figure 21: South End Median 10-Year-NPV of Energy Savings for ECM2 ($1000)

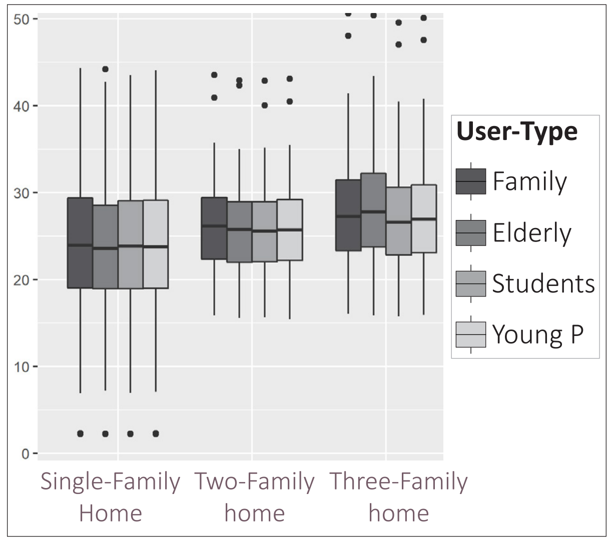


Figure 21 shows the range of 10-year energy savings NPV for ECM2 by land use and user in the Soth End. Little variation between land uses reflects minor building size differences.

Figure 22: Dudley Traingle Median 10-Year-NPV of Energy Savings for ECM2 ($1000)

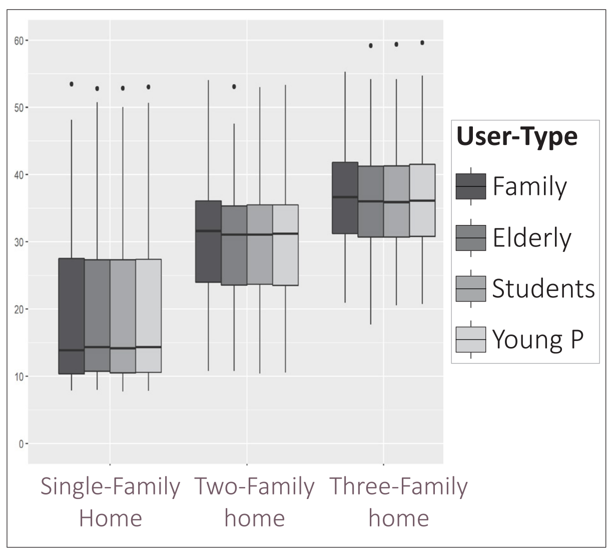


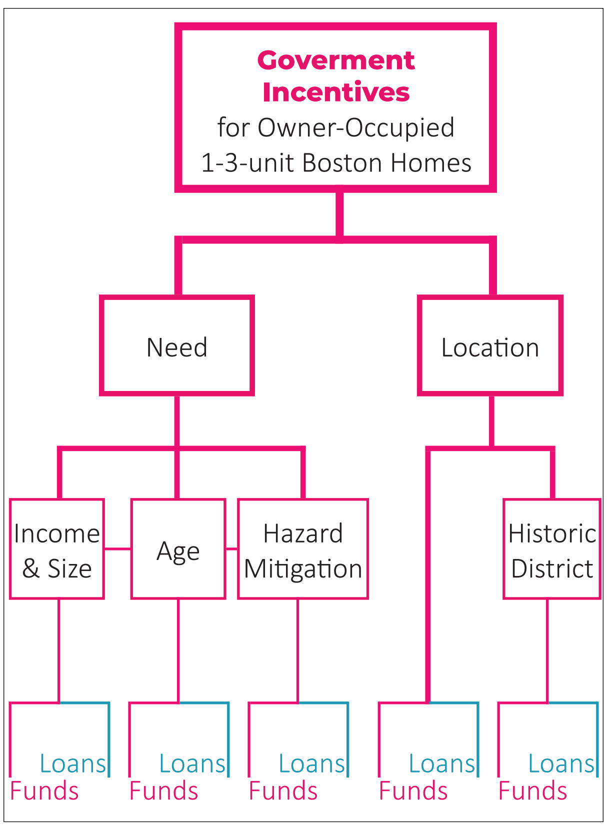
Figure 22 shows the range of 10-year energy savings NPV for ECM2 by land use and user in Dudley Triangle. It shows that 2-3-unit family homes incur significantly more energy savings over time than single-family homes.

STEP 3: ASSIGN USER-SPECIFIC INCENTIVES

This step continues to develop a user-specific benefit profile for each building, by adding the sum of all available incentives to each user. Similar to step 2, each building is assigned four user-specific incentive profiles, one for each user-type.

Figure 23 shows the Government incentive allocation tree used in this analysis. The total Government incentive available for each user are affected by location variables, such as building type, and land use; and by need-based variables such as household income & size, age of householder, and ownership type. For a detailed description of all government incentives modeled see Appendix B. The following paragraphs will describe the incentive allocation process.

Figure 23: Goverment Incentives Allocation Tree for 1-3-unit family homes in Boston



(Not Inclusive of affordable housing programs such as LEAN, LIHEAP and ABCD)

Starting with location-based government incentives, each parcel is evaluated for government incentives available for 1-3-unit family homes in Boston, and where applicable, neighborhood-specific incentives are calculated. Location data is drawn from the City of Boston Tax Assessor data for 2016, the City of Boston Neighborhood boundary, and the City of Boston Historic District zoning overlay. Primary location-based incentives are federal and state tax credits and exemptions for solar panels installation, Mass Save energy efficiency grants, rebates and discounts for 1-4-unit family homes, and historic renovation tax credit. Location-based incentives are applicable by parcel and are not affected by the demographic characteristics of the people living in the building.

Next, each user is evaluated for need-based government incentives. The UBEM user classification defines the household size and age-range for each user-type. Household income is estimated at the block level, drawing median household income information from the 2013-2017 American Community Survey by block. Together these variables determine eligibility to need-based government assistance. Primary need-based incentives include the Mass Save income-eligible and enhanced incentive programs and the City of Boston Home Repair program. In addition, there are several income-age-based incentive programs available for seniors and children. Seniors can receive additional assistance from the state and city. Income eligible households with a child under six can receive assistance from the city to abate hazardous materials. For the purpose of this model, the user-type family is assumed to include a child under six. Need-based incentives are unique to user-types and income. Overall, household size and the income-age-based programs create the main variations between the benefits bundles available for each user-type.

At the end of this step, the total location-based and need-based incentives are calculated for each user, resulting in four incentive profiles for each building, corresponding to the four user-types. All cash incentives received from discounts, rebates, tax credits, tax exemptions, and grants are summed to one category titled incentive-funds. All 0% loan incentives, available from different agencies for different purposes, are summed under one category titled incentive-loans.

Figure 24 shows the results of incentive-funds allocation to South End buildings. Since the majority of households in this area are higher income, they are not eligible for need-based assistance, which explains why the benefit profile of users for each land-use is almost identical. Differences in the total amount of incentives available for different land uses are caused by variation in building size, since incentives are responsive to implementation costs, which are correlated to building size.

Figure 25 shows the results of incentive-funds allocation to Dudley Triangle buildings. Similar to South End results, the larger the building size, the higher the total amount of available incentives. In contrast to the south end, Dudley triangle households are low-medium income, which makes them candidates for need-based government incentives. The boxplot shows that for the same building and income levels, the user-type family is eligible for the most incentives, and the user-type elderly is eligible for the least incentives. The reason for the low amount of incentives available for the user-type seniors is that seniors are modeled as a 2-member household, in comparison with the user-type family, which is modeled as a 4-member household. It means that for the same income level, it is possible that seniors do not meet the eligibility criteria for low-income assistance while families do. User-type students and user-type young professionals are modeled as 4-member and 3-member household respectively, and for the same income level, there is no variance for the total amount of incentives available to these groups.

Figure 24: South End Median Incentives Per Building By User-Type And Land Use ($1000)

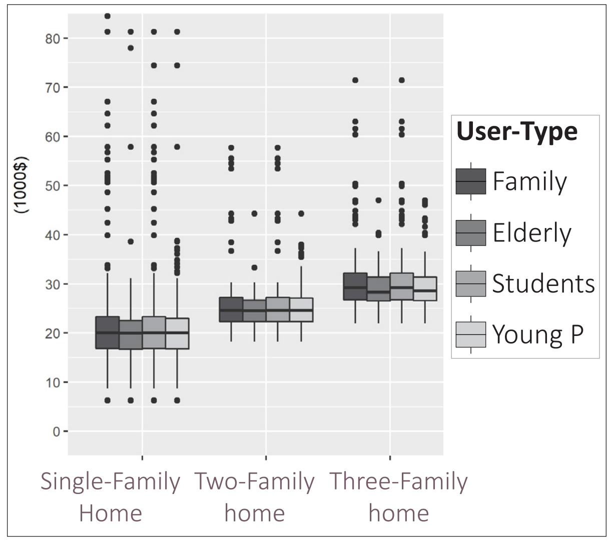
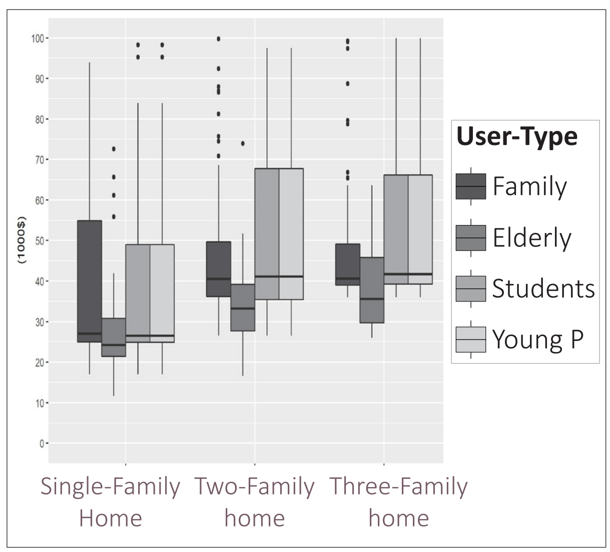


Figure 25: Dudley Triangle Median Incentives Per Building By User-Type And Land Use ($1000)



STEP 4: ANALYZE THE FINANCIAL FEASIBILITY OF IMPLEMENTATION

This step uses three tools to analyze the financial feasibility of investment: Net Present Value (NPV), Multiple on Investment (MOI), and Payback time. The NPV reveals whether the benefits outweigh the cost over a selected time period, the MOI is indicative of the investment performance, and the payback time helps understand the amount of time needed for the annual revenue to pay for the upfront investment. Similar to previous steps, these calculations were applied four times to each building, once for every use-type.

For each user-type-building combination, NPV was calculated for year-0, 3-years, 5-years, 7-years, and 10-years. The calculation deducts the total retrofit costs from the total benefits available, where benefits are the sum of government incentives and the NPV of energy savings for the selected time period. The exception is year-0 where benefits there are no energy savings and only government incentives are included. If the result of the NPV calculation is positive, the investment is considered feasible or affordable.

For all parcels that tested positive for a 10-year period, MOI was similarly calculated for each user-type-building combination. The Calculation divides the total energy savings for the selected time period by the total cost to the owner, which is the retrofit cost minus the government incentives. Low MOI results indicate weak financial performance, especially in comparison to investment options with higher MOI.

Payback time is calculated for all user-type-building combination by dividing the cost to owner by the annual energy savings. This calculation assumes that households will want no changes to their annual expenses, and the return on the loan should be no greater than the amount of money they already pay for energy expenses. The shorter the payback-time, the faster households will see a return on their investment.

Lastly, the results of the 10-year NPV calculations for each user-type-building combination were correlated to the neighborhood demographics, to estimate the percentage of households that can afford a retrofit out of the total households in the neighborhood.

Figure 26: South End 10-year NPV ($1,000)

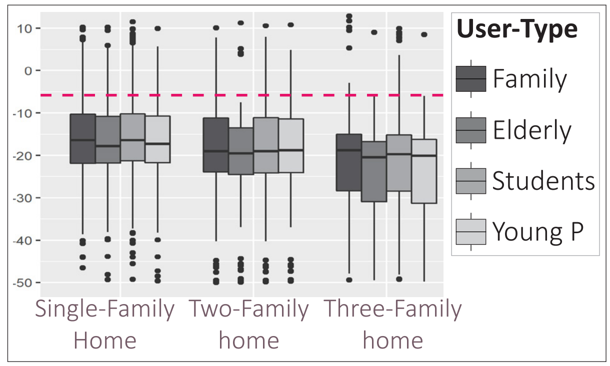


Figure 26 shows that the overwhelming majority of South End household do not have sufficient funds to afford a deep retrofit.

Figure 27: Dudley Triangle 10-year NPV ($1,000)

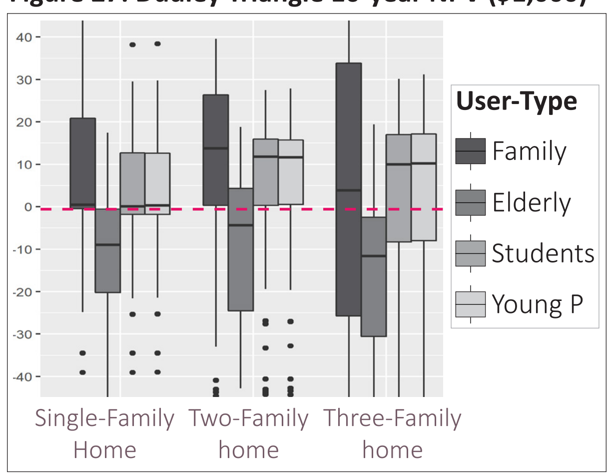


Figure 27 shows that the majority of households in Dudley Triange have sufficient incentive to retrofit their home, excluding the user-type seniors, which can be explained by their limited eligibility to need based incentives. Uncertainty is caused by variation in building size, variation in necessity to pay for abatement costs and variation in eligibility to need-based incentives.

Figure 28: South End Payback time (years)

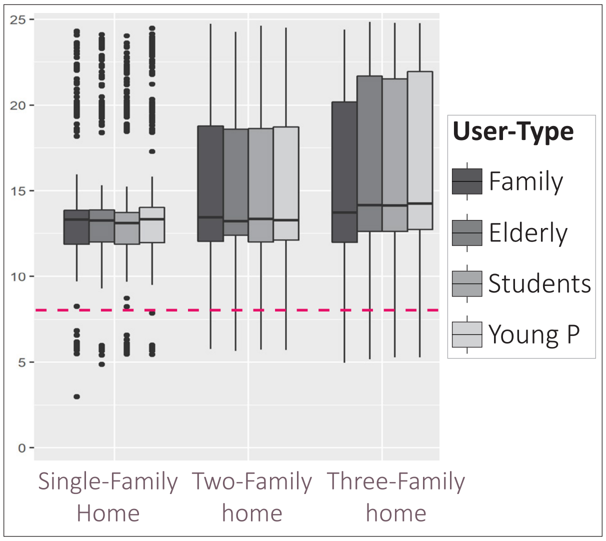


Figure 28 shows that the majority of South End proerties will need more than 10 years for the benefits to outweigh the costs of retrofit implementation, with the median payback time ranging between 13-14 years across all buildings.

Figure 30: South End 10-Year MOI for proerties with positive NPV

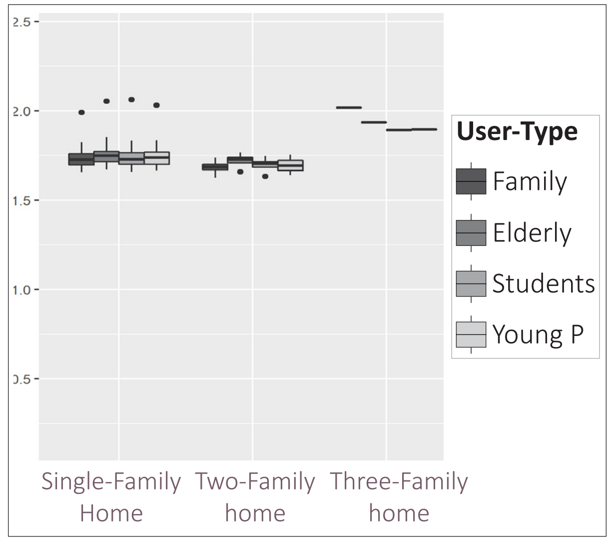


Figure 30 shows that even for propeties that have positive NPV, the investment performance is weak, and it is likely that other avenues for investment are more profitable.

Figure 29: Dudley Triangle Payback time (years)

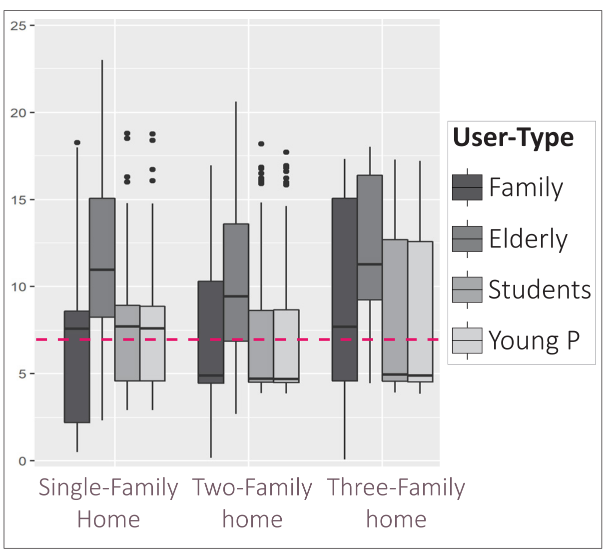


Figure 29 shows that with the exception of seniors, the majority of households living in 2-3-unit family homes have a payback period shorter than 7 years, and the majority of single-family homes have a payback period shorted than 10-years.

Figure 31: Dudley Triangle 10-Year MOI for proerties with positive NPV

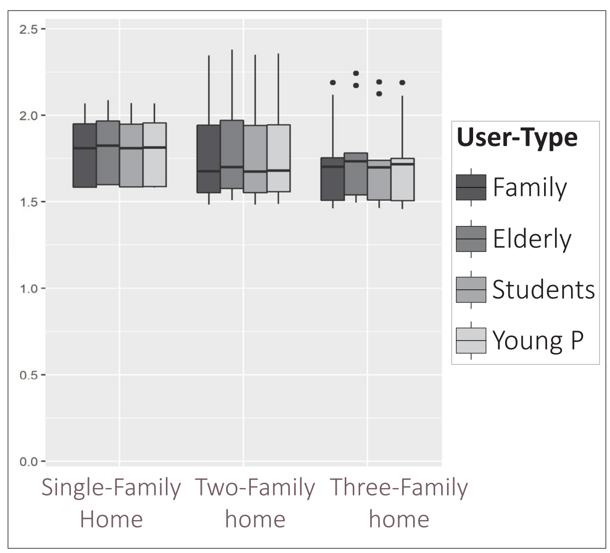


Figure 22 shows the range of 10-year energy savings NPV for ECM2 by land use and user in Dudley Triangle. It shows that 2-3-unit family homes incur significantly more energy savings over time than single-family homes.

05 Results

Analysis of the Current State of Retrofits in Boston

Figure 32: South End Percentage of 1-3-Unit Homes with Positive NPV for Five Time periods

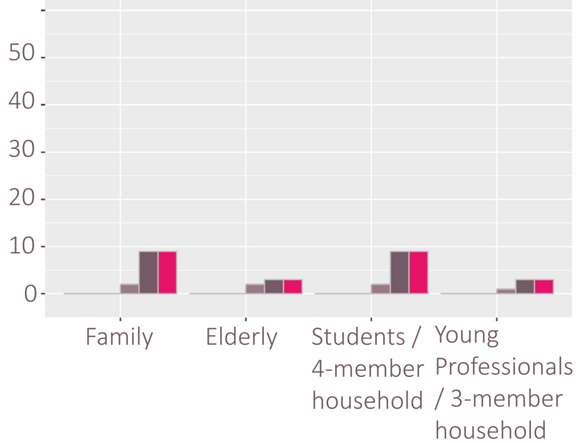
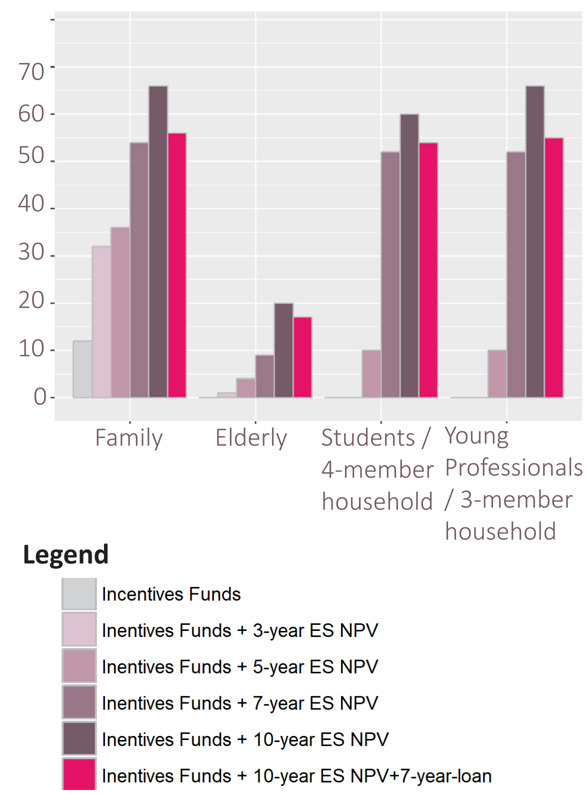


Figure 33: Dudley Triangle Percentage of 1-3-Unit Homes with Positive NPV for Five Time Periods



NEIGHBORHOOD RETROFIT POTENTIAL

Results show the dramatic impact of retrofit affordability on the ability to meet city-wide carbon neutrality targets. Figures 34-35 show that in both neighborhoods, energy efficiency and generations measures can reduce over 70% of the total energy consumption of 1-3-unit family buildings. However, this potential will not be met if people can not afford to pay for this change.

In the South End, over 90% of the buildings have insufficient incentives to retrofit (figure 32). Even if the limited subset of building that can financially afford to retrofit proceeds with implementation, the impact on the total energy consumption is minimal and less effective than if all buildings had to comply with a Mass Save audit which installs efficient lights and seals drafts (ECM1). The modeled minimal financial feasibility to retrofit buildings in the South End is consistent with limited participation in Mass Save programs for this area between 2014-2017.

In Dudley Triangle, over 50% of the buildings have sufficient incentives to implement retrofits (figure33), and if they take action, they can reduce the total energy consumption by half (figure 35). However, while participation rates in the Dudley Triangle are higher than the South End's participation rate, they are still significantly below the potential to retrofit building in this neighborhood.

A closer look at the potential to retrofit by user group reveals that for the same income levels and building type, the larger the household size, the more likely it is to be eligible for government incentives (figure 32-33). This explains why the user group elderly (2-member household) receives significantly less financial support than other groups. It was surprising to receive these results because several government programs target low-income elderly population. One explanation for this result could be that the elderly population in the Dudley area might be earning just a bit above the maximum amount to qualify for financial assistance.

Figures 32-33 are also indivitive of the amount of time needed for a retrofit project to provide a return on investment. In the South End, not only that Government incentives are insufficient for all user groups, but also that the combination of energy savings and government incentives provides a positive NPV only for seven years and longer. In Dudley Triangle, a small percentage of family-occupied buildings qualify for full government assistance with no additional cost to owners. For all other properties, the feasibility of implementation grows with time, with the majority of projects achieving positive NPV after seven years, and nearly two-thirds of the buildings achieving positive NPV in 10 years. The caveat however, is that Mass Save 0% loans are available for a maximum of 7 years, meaning only a small fraction of buildings with a payback period greater than 7 years will be able to afford the loan.

Overall, results reveal that low-medium income households have an underutilized potential to participate in retrofit programs. Results also show that the currenct incentive scheme will not motivate the majority of the population, thus creating a conflict between the city's mission to achieve carbon neutrality by 2050 and its policies to achieve this target.

Figure 34: South End Total Annual Energy Consumption (1,000,000 KW) of 1-3-Unit Homes

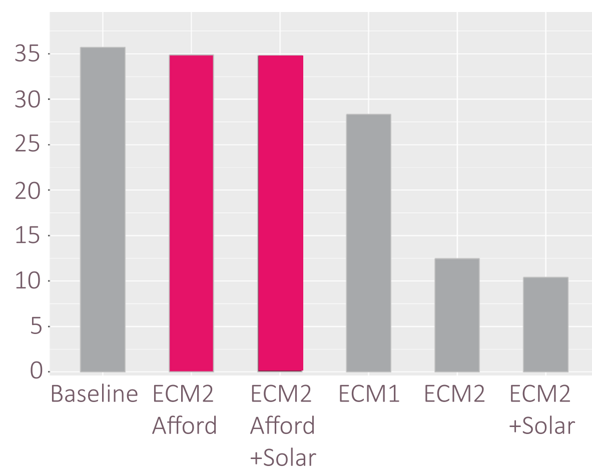


Figure 36: South End Total Annual Energy Expenses ($1,000,000) of 1-3-Unit Homes

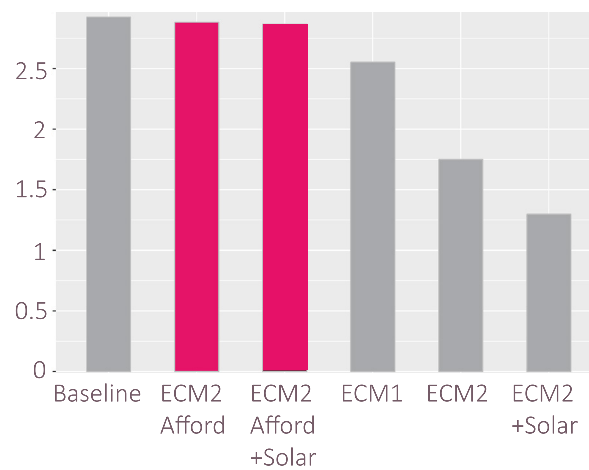


Figure 35: Dudley Triangle Total Annual Energy Consumption (1,000,000 KW) of 1-3-Unit Homes

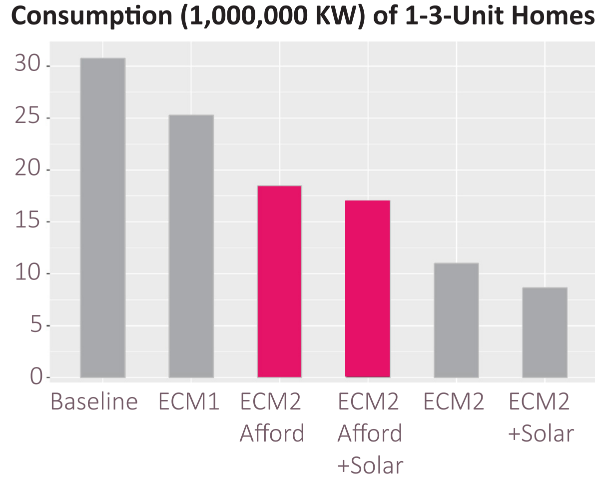
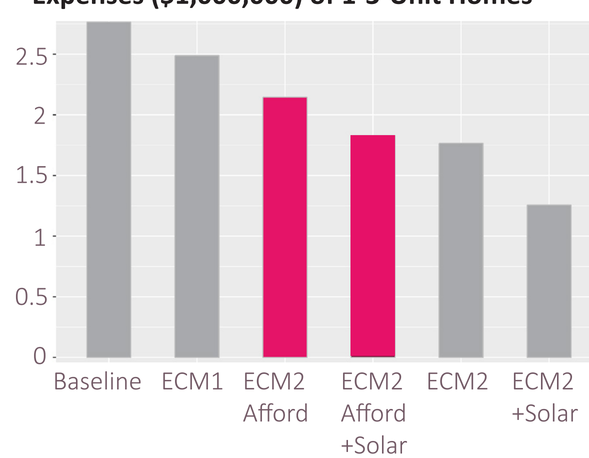


Figure 37: Dudley Triangle Total Annual Energy Expenses ($1,000,000) of 1-3-Unit Homes



CITY-WIDE NEED-BASED ELIGIBILITY TO INCENTIVE PROGRAMS

Primary need-based incentive program in Boston are provided by the state Mass Save income eligible and enhanced programs and by the City's low-income and medium-income programs. Eligibility to these programs is defined by household size, household income, and in some cases householder age. By defining a user-type, policy makers can better understand how many people are eligible to these programs for an urban area, such as a neighborhood or an entire city. The figure below derives information from the 2013-2017 American Community Census data by block to create an eligibility profile per user-type by urban area. The calculation was made by summing the amount of households by income eligibility and then using weighted averages to determine the proportion of specific user types out of the entire population. Results show the eligibility "pulse" for each area by user-type, ownership and incentive program. Key take aways from this analysis are that low income programs are underutilized in Boston for the selected user-types, and that when ownership is a requirement, eligibility is cut by more than 50%.

Figure 38: Percentage of Households of user-type Elderly eligible for primary need-based incentive programs by urban area

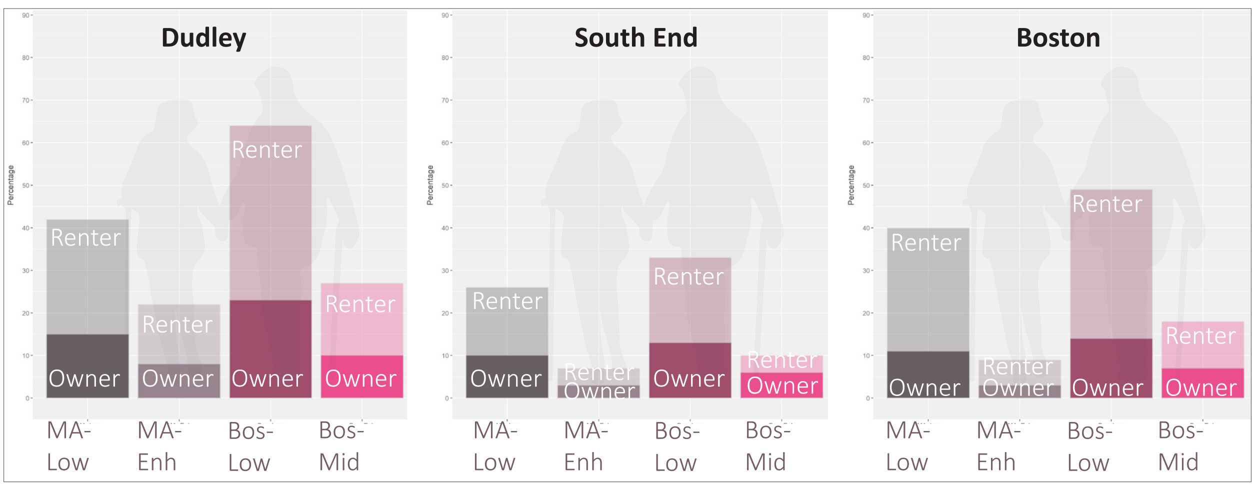
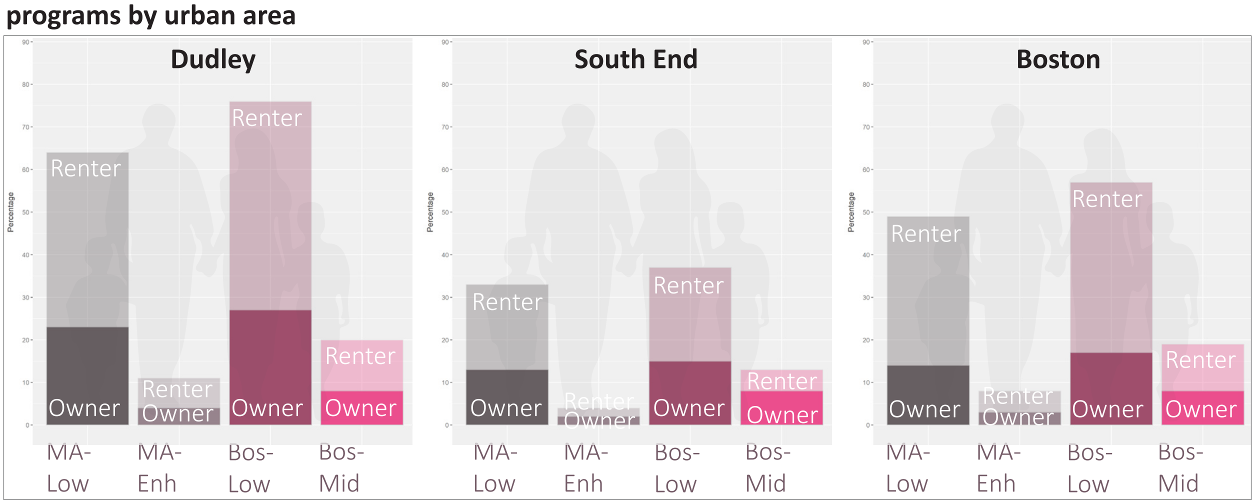


Figure 39: Percentage of Households of user-type Family eligible for primary need-based incentive programs by urban area



DECISION-SUPPORT VISUALIZATION TOOLS

The data visualization mock-ups presented in figures 40-41 respond to the existing knowledge gap with regards to the availability of incentive programs to support retrofits in Boston. Interviewees across all sectors expressed a desire to have a one-stop shop for government incentive programs, that provides information about the specificity of available incentives by user-type and location.

Existing tools to provide information about incentive programs are agency-specific, thus lacking information about the ability to receive assistance from multiple agencies. In addition, tools are not user-specific, and individuals seeking assistance have to spend a significant amount of time researching incentive programs to understand if they meet the eligibility criteria. Thus, the lack of coordination between different agencies and the lack of user-specific information act as a barrier to the design of retrofit policies as well as to participation in retrofit policies.

To address these challenges, this research developed two mockups for decision support tools. These tools respond to the primary allocation criteria of government incentives for energy efficiency and energy generation: income, age, household size, building type, and location. Based on these criteria, this research developed a filtering and classification script to identify available incentives by household and building type. This script serves 1-3 family homes in Boston by scanning all available incentive programs and providing a building and household specific output.

Figure 40 shows a tool designed for policymakers, and figure 41 shows a tool designed for individuals. The difference between the two is that the first draws demographic information from the census block to provide information about how policies affect pre-defined users, while the second tool requires individuals to manually insert demographic characteristics to receive specific information tailored for their eligibility and needs.

Figure 40: Decision-Support tool for policy designers

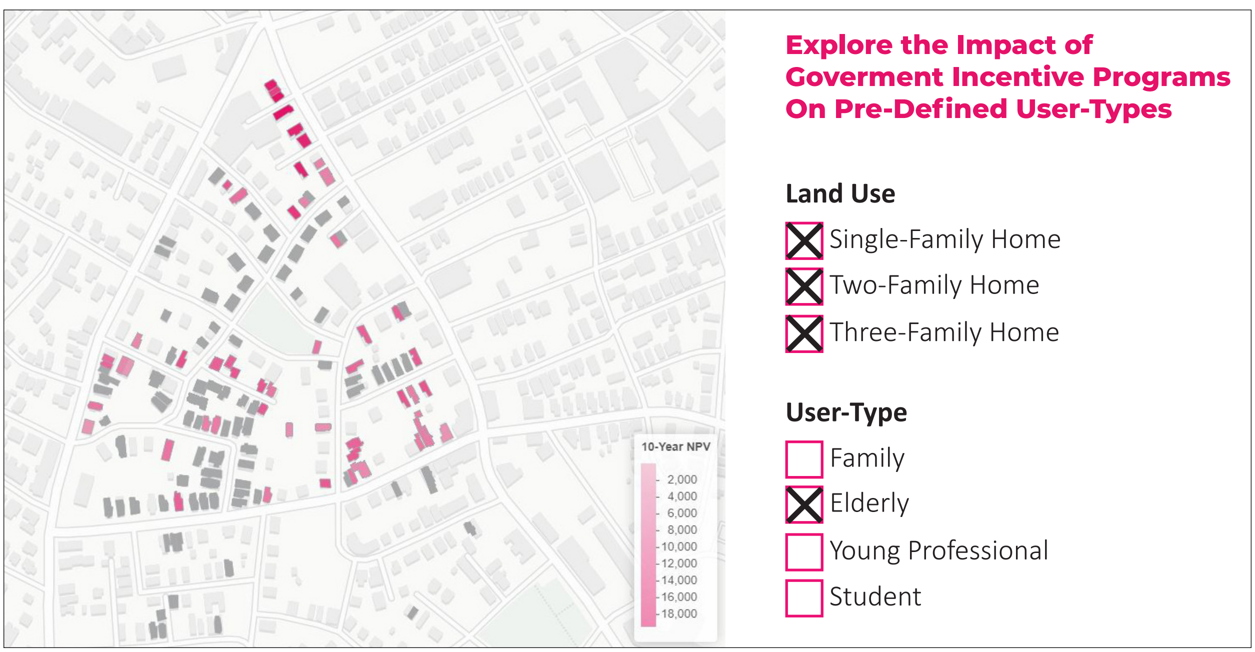
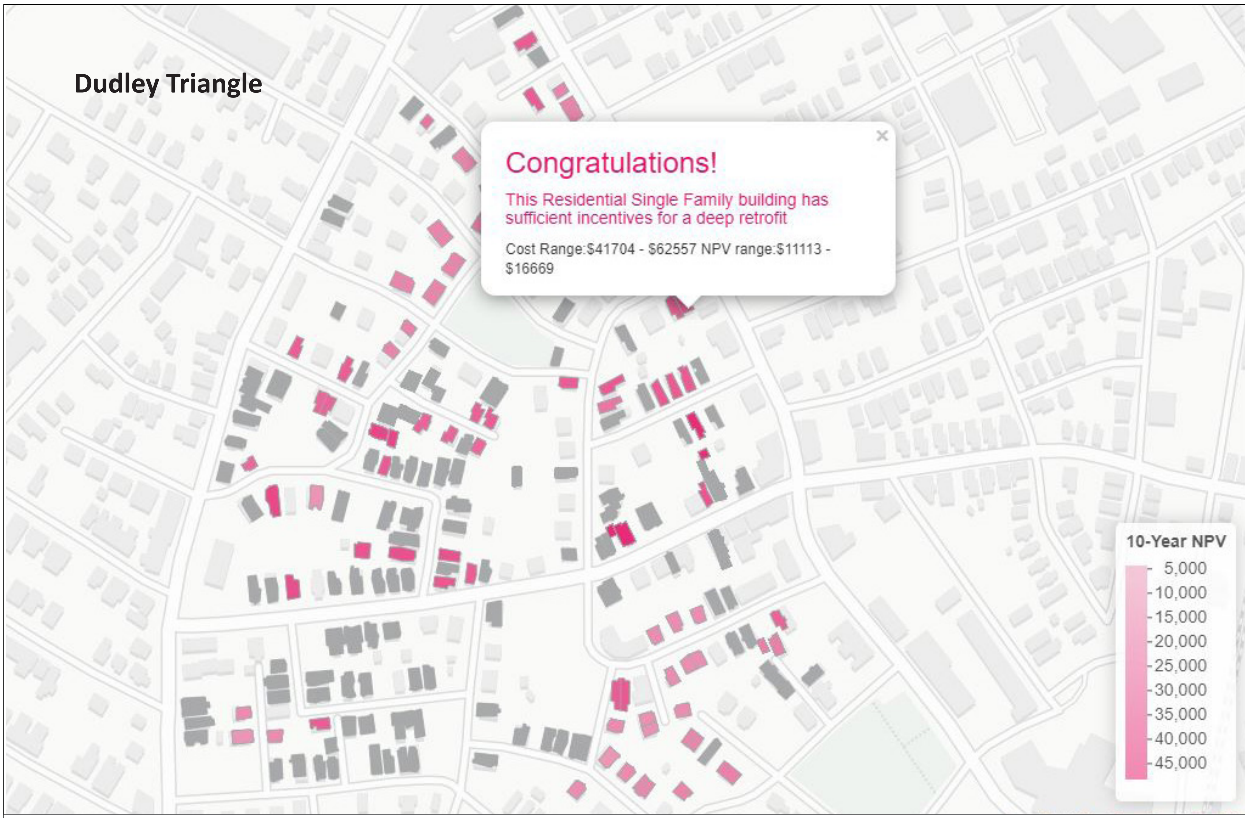


Figure 41: Decision Support Tool For Individuals



Congratulations!

Based on the information you provided, you are eligible for the following incentive programs:

Federal and State Tax Credits and Exemption for Solar

Mass Save Income Eligible program to provide at no cost audit, insulation, and HVAC replacement as Necessary.

City of Boston Home Repair Assistance

City of Boston Lead Free homes

Mass Save 0% Loan

You are advised to get an energy audit for your house at no cost from Mass Save to have a better understanding of the costs and programs that are available to you. The following are general cost estimation ranges for your area and building type:

Retrofit cost: $45,000- $60,000

Revenue From Energy Savings: $10,000-$15,000 (10-year NPV)

Revenue from Incentives: $25,000-$30,000

Total Cost (minus Incentives): $15,000-$35,000

Payback time: 7-10 years

Multiple On Investment: 1.2-1.7

Find out which Government Programs are available for your location and Household needs

What is Your Household Size?

- [ ] 1
- [ ] 2
- [ ] 3
- [X] 4
- [ ] 5

Are Members of Your Household This Old?

- [X] Younger than 6 years old
- [ ] Age 60- 62
- [ ] Age 62 and over

What is Your Household Annual Income?

0 — $200,000 and over

$60,000

What Type of House Do You Live In?

- [X] Single-Family Home
- [ ] Two-Family Home
- [ ] Three-Family Home

Choose your location on the map! to discover location specific benefit programs

Both tools demonstrate that it is possible to create an informational web platform to communicate the specificity of available government incentives by household and building type. The strength of the tool designed for individuals is in connecting residents with incentives from federal, state, and municipal agencies without asking people to register to provide private information or to invest a considerable amount of time in filling a form.

While It is not possible to provide residents with accurate information about the financial feasibility of their specific project, it is possible to provide residents with a range of cost and energy savings that are typical for their area, building type, and user characteristics.

Altogether, this analysis and visualization tool provides a necessary service to citizens at a preliminary stage, that will help individuals better understand their financial options and pathways to retrofit implementation.

How to use this tool?

First, fill in the information on the right to determine the specificity of available incentives for your location and household profile. Next, click on the building you're interested in to discover the range of costs and benefits typical for your location and household profile. It's important to note that this tool is designed to provide cost-benefits estimates and does not substitute an energy audit by a professional. Lastly, based on the information you provided, you will see a list of government programs you are likely to be eligible for.

06 Discussion

Interpretation of Results and Insights From Interviews

For households without access to need-based assistance, there is little to no financial feasibility to benefit from implementing a retrofit project if incentives and energy savings are the only source of financing. The low participation options modeled for the higher income households in south end is consistent with Mass Save data about low participation in energy efficiency programs for this area, which amounts to 1.6% of all households between 2014-2017. Under the current incentive scheme for the South End, if all the households that can afford a retrofit will implement it, the reduction in the total energy consumption for the neighborhood will be minimal, and less than the effect that a Mass Save Energy Audit for all buildings will have.

For households eligible for need-based assistance, there is a significant gap between the current rate of participation in retrofit incentive programs and the potential to benefit from them. This is particularly the case for households entitled to benefits from different agencies, such as the user-type family. With four household members and a child under 6, low-medium income families can receive additional assistance from Mass Save as well as from the city of Boston Department of Neighborhood Development (DND). Under the current incentive scheme for the Dudley, if all the households that can afford a retrofit will implement it, there will be a 50% reduction in the total energy consumption for the neighborhood.

The following section will discuss possible explanations for these results under these categories: Finance, Regulation, Organizational Capacity.

FINANCE

Several financial assumptions explain the gap between the percentage of people who can potentially benefit from a retrofit project and the actual participation rate.

First, in order to receive government incentives through the Mass Save program, residents have to make an upfront investment, that will be returned partially or in full after several months. Low-medium income households may not have sufficient funds to make the initial investment or the ability to take a bridge-loan for that period. Inability to perform this initial steps prevents participation.

Second, the model shows that for households with need-based assistance benefits accrue over time, making it financially feasible to participate if the people who live in the house intend to stay in the same place for several years. If people take a 0% interest loan to finance the project and have monthly returns at the rate of their energy savings, they will only see financial benefits from the project once the loan is paid. For low-medium households in Dudley, that time period is 5-10 years. If people face uncertainty at work, they might be reluctant to take a long-term loan.

Third, for loans that have a fixed time period, monthly returns can be larger than monthly energy savings. This means that if a project has a positive 10-year-NPV, but the only loan available is through Mass Save with a fixed return period for seven years, the monthly returns will exceed monthly savings, increasing the resident’s expenses for the 7-years it takes to return the loan.

Fourth, 0% interest loans are available through multiple sources for different energy efficiency measures. However, in some cases those loans come with strings attaches to specific contractors, which make it more challenging to use financing from multiple sources.

Fifth, even for the long-term 10-year period, the Multiple On Investment is low for all households with positive NPV. This means that if the main driver for investment is financial gains, many other options are much more profitable than a retrofit project.

Lastly, there are currently no incentive programs to assist properties that are located in a flood risk overlay.

To conclude, the current financing mechanism imposes higher barriers to entry for people who do not have sufficient funds for upfront payments and a long-term interest in holding the property.

REGULATION & PERMITTING

While there is no regulation to support retrofitting, some regulation can be cost-prohibitive. For renovation projects that trigger the long review process, compliance with the state building code for ADA and Fire and Safety may incur significant costs that outweigh the benefits of the project. Local cost prohibited regulation applies to historic districts, where regulation to maintain the exterior façade and windows is cost prohibitive.

ACCESS TO INFORMATION

The ability to participate in government programs that incentivize retrofits depends on the ability of people to understand what is being offered, what is the process for participation, how participation will affect them financially, and what will they gain from participation. Currently, no one-stop shop provides this information, and it is challenging to create a compelling argument towards retrofit implementation with missing information. This knowledge gap is exacerbated for non-native English speaking populations, which are not able to benefit from the partial information that is available.

ORGANIZATIONAL CAPACITY

In addition to a knowledge gap, households also have to dedicate a considerable amount of time to engage with education about this process, fill applications, stay at home for contractor visits, and re-organizing their house for extensive renovation. This opportunity cost of time loss is not calculated in this model, but it is an additional barrier for people who cannot take time off work.

Moreover, implementation also requires managing a team of contractors and overseeing their work. Reviews of Mass Save approved contractors have been mixed, with some interviewees reporting satisfaction with service and others reporting utter dissatisfaction and cancellation of work. For people inexperienced with the construction sector, managing a construction project can be alienating to the point of preferring not to take any action.

Interviewees across all sectors emphasized organizational capacity as a key barrier for individual home owners. Lopez, the Renew Boston Program coordinator, described resident confusion over which programs they should reach out to, and difficulties in coordinating service. Flynn, the DND Home Center Director, explained that lower-income residents are struggling to understand the financial implication of renovations and some population are intimidated by the necessity to manage a construction team. Architects shared that retrofit projects with uninformed project managers result in lower quality of implementation, due to high barrier mitigation costs that were not supported by incentives.

To conclude, current government incentive programs place the burden of project management on individuals who need to be informed, available and capable of managing a construction project. The only program that addresses some of these challenges is the DND Home Improvement loan program, that assigns a project manager to every project they approve.

07 Recommendations

To Accelerate Retrofits in Boston

SHORT-TERM

In the short term, the city can act fast to provide immediate assistance to low-medium income residents living in 1-4 unit homes that have positive long term NPV but high barriers to participation. Quick fixes include Improved access to building and household specific information, expansion of the DND Home Repair program to support retrofits with management and financing, and piloting a community-led program to explore more comprehensive city-wide efforts.

1. Bridge the Knowledge Gap

The most straightforward and fundamental challenge to fix is information access and transparency. It is the first step towards achieving all other goals, and it is within reach, as demonstrated by this study. The city should create an informational web platform to provide all citizens with individualized information about public resources available for them and education about the retrofit process. The website should take a resident step by step, be communicative, and not infringe on privacy. Achieving similar goals for the solar sector, Mapdwell serves as an excellent example of a building-specific information platform. It is easy to use, communicative and effective in providing a cost-benefit analysis that takes into consideration implementation cost, available government funds and annual revenue from energy generation. If a similar website existed to support retrofit decision making, it would bridge the knowledge gap, providing valuable information to residents and policy designers.

2. Pilot Community-Led Programs to Bolster Low-Medium Communities' Organization Capacity

Next, the city can initiate a program to target low-medium income owner-occupied households that have sufficient incentives to benefit from retrofit implementation but have high barriers to entry. Since barriers for this audience are multi-layered, a community-based approach can have better success chances than an informational campaign. Both national and international experience with community-based approaches has revealed that this framework enables widespread adoption by addressing community-specific barriers to participation. Community organizations are trusted by their community and have better insights into what will work best for their neighbors. A pilot program with an influential organization can help the city develop a scalable framework that will apply to other neighborhoods. One example of such a collaboration can be with the Dudley Street Neighborhood Initiative (DSNI). This organization manages the Dudley triangle community land-trust and is well positioned to support its residents with long term planning to improve the quality of life in the area.

3. Improve Access to Financing options

1. Provide Upfront financing (0% loan) to bridge the time gap between investment on energy efficiency measures and receipt of Mass Save rebates. This step can unlock opportunities for low-medium income householders who are not able to get a loan for the initial investment. In cases where the rebate is lower than the investment, the city can extend the 0% loan

service to apply to the households in need of upfront financing in lieu of future energy savings.

2. Coordinate financing with Mass Save to ensure the monthly return is no larger than the current expense on utility bills. For households that have a longer payback than seven years, Mass Save loans that can extend only up to 7 years, cannot provide sufficient assistant because they will translate into a monthly return that people cannot afford. The city already offers better terms for loans through the DND Home Center programs, and financial coordination can remove barriers to participation.

LONG-TERM

In the long term, the city needs to consolidate its efforts by improving interagency coordination, simplifying the retrofit process, removing regulatory barriers and improving access to public funds and financing options.

1. Consolidate Government Efforts

The city of Boston already has several successful inter-agency collaborations that target the built environment, such as the ADU initiative, the Home Repairs 3D Help, and the BREATH Easy at Home program. To accelerate retrofits, the city needs to create an easy-to-follow process for residents, where they do not need to consult with every agency individually. At a minimum, this collaboration should include the Environment Department to manage and measure the success of energy efficiency and energy generation incentive programs, and better coordinate efforts with the state. It should also include the Department of Neighborhood Development (DND) to connect with citizens and adapt programs to their needs, the Inspectional Services Department (ISD) to streamline the permitting process, the Planning and Development Authority (BPDA) to create a retrofit zoning overlay, and the Department of Information Technology (DOIT) to create effective communication and information platform. Together, these agencies can transform the retrofit experience in Boston, accelerate implementation and create new jobs.

2. Create a Retrofit Zoning Overlay To Remove Procedural Barriers and Incentivizes the Creation of New Housing + Retrofitted Homes

Considering households that have insufficient incentives to retrofit their house, the city can either find additional public funding sources to support them or create Real-Estate incentives that will enable the private sector to supplement funds. Enhancement of the ADU program to allow the construction of additional units as needed to support a whole building retrofit, can both increase housing units in-demand areas and incentivize developers to initiate and manage retrofit projects. A zoning overlay plan can identify areas where this process will be most effective and provide neighborhood-specific design guidelines to address both mitigation and adaptation goals. This plan should also study the impact of retrofit implementation on renters and affordable housing and create measures to prevent gentrification.

3. Streamline Financing Options

For households that do have sufficient incentives to retrofit but high barriers to entry, the city can work with communities to design a one-stop-shop for retrofits, that provides knowledge, management, and financing. As a public organization, the city is well positioned to plan for the long term and shift the responsibility and risk from the individual to the city government. One way to do this is to create an agreement where the residents pay a fixed fee for energy services for a 10-year period that is no larger than their current energy bill in return for retrofit implementation. The gap between the price residents pay post-implementation, and the actual energy price will pay for the renovation over time. This mechanism will provide reassurance for residents that they will get a better housing quality without unexpected and unfordable costs.

08 Limitations + Next Steps

LIMITATIONS

1. Meaningful at the neighborhood-urban scale only

Both Energy Savings and Cost Assessment Analysis are approximated at the individual building level and provides valuable insights only when aggregated. This type of research is meaningful for urban policy decision making, but other tools need to be developed to support individual decision making support.

Due to data discrepancy between the parcel by parcel Tax Assessor Data and the block size census data, information about demographics is approximated based on the distribution of demographic characteristics by block. It means that the information makes sense at the neighborhood scale but cannot be precise at the single building scale.

2. Lacks Model Validation

The data analyis establishes a workflow to assess the impact of goverments incentives and energy savings on the ability to financially afford retrofit implementation. At the same time, the inputs for this workflow have not been validated. Both energy savings and retrofit costs should be calibrated according to real data and a margin of error should be added to the model.

3. Need to explore additional user groups

There is a high correlation between the user groups used for this research and government incentive allocation, but they do not cover the entire range of households in the neighborhood, and especially not the 1-2 member households.

This research explores incentives and energy savings as the only source of revenue for a retrofit project. This is true for owner-occupied properties, but the calculation for rented properties is more complicated and should include revenue from the rent that reflects the increased value of the property due to offering better living conditions. Thus renter-occupied properties might have additional revenue sources not explored in this research.

4. Doesn’t Include Building Electrification

The 2019 Carbon Free Boston report identifies both Building energy efficiency and electrification as crucial to meeting Boston’s carbon neutrality targets. Since this report has only been released recently, there weren’t any government incentives to consider for this research. Future research should incorporate a methodology to study the costs and benefits of building electrification.

5. Evaluates the Same ECM for all Buildings

The Existing UBEM evaluated different energy conservation measures and aggregated them into two scenarios: ECM1 and ECM2, which reflect minimal interventions and deep retrofit respectively. The cost benefit analysis presented in this thesis applies to the deep retrofit scenario and assumes that every building needs to implement all the energy conservation measures identified by the existing UBEM ECM2. Future research can resolve this limitation by applying a cost-benefit analysis for energy conservation measure and not by an entire scenario.

6. Financial Analysis Depends on Current Energy Prices

Energy savings reflect the gap between the expenses of the current consumption and the expenses after a retrofit project has been implemented. However, expenses respond to the price of electricity and gas. The current high electricity prices incetivize investment in solar panels that directly reduces the electricity expenses, while the current low gas price is a barrier for electric HVAC systems in comparison with gas HVAC systems. In addition, overall increase to energy prices will makes investment in energy efficiency and generation measures more beneficial, while a decrease in energy prices will have the opposite affect.

NEXT STEPS

1. Incorporate user perspective

This research incorporates the perspectives of policy designers, developers and architects, but does not include resident perspective. Future research can be conducted in partenship with community partners to better understand their barriers to participation and which type of tools, programs and communication will be the most effective in encouraging and supporting retrofit implementation.

2.Incorporate Behavioral Economy variables

Investment in retrofit project is a financial decision-making process that can benefits from behavioral economic insights. For example, the opportunity cost of time lost should be included in retrofit cost calculation to account for the organization labor required from individuals and the time they need to take off work. Additionally, behavioural economy perspectives are more suited to explore perceptions of risk and uncertainty.

3.Incorporate Long Term Health Impacts

Previous research has established that poor housing quality has adverse impacts on health. These impact should be quantified and added as a social good at an urban scale.

09 Appendices

Appendix A: Data Sources

The complete retrofit data set needs to inform users of the necessity to retrofit a property, the estimated cost of the proposed project, and the available financial resources to support implementation. For this purpose, the following data sources are used:

1. Urban Building Energy Modeling (UBEM)
Described in next section.

2.City of Boston tax assessor data for 2016
Includes information about land use, ownership, year built, year remodeled, living area, exterior material, and other physical properties by parcel.

3.City of Boston 36inch sea level rise 1pct annual flood
Area of potential coastal and riverine flooding in Boston under 36-inch in 2070s scenario at high tide and in the event of storms with an annual exceedance probability (AEP) of 10 and 1 percent.

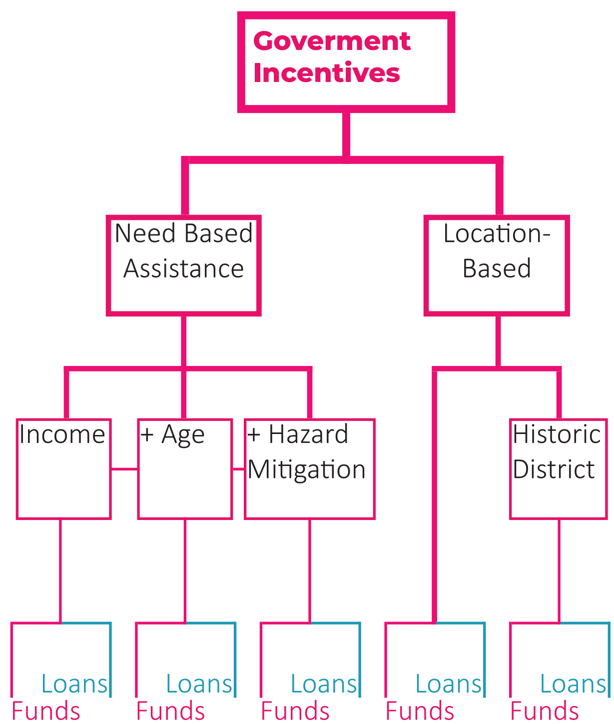
4. City of Boston Neighborhoods
Some City incentive programs are provided by neighborhood, such as the ADU program, which was piloted in Mattapan, East Boston and Jamaica Plain.

5. City of Boston Historic Districts
Reveals which areas are under strict regulations to maintain an historic façade.

6. American Community Survey 2013-2017 by block for Suffolk County, MA
Demographic information by block, includes information about householders income and age aggregated at the block level.

7. Federal, State and Municipal incentives to support retrofits.
Study of available incentive programs through government website and interviews with policy designers in the City of Boston. There are a 128 federal and state energy efficiency incentives program applicable in MA, out of which 60 target residential properties and 28 are applicable in Boston. In addition to those, the City of Boston offers several incentive programs for population in need. Each of this programs has a different eligibility and income criteria and a different application process.

Incentives allocation for 1-4-unit homes



(Not Inclusive of affordable housing programs such as LEAN, LIHEAP and ABCD)

Appendix B: Government Incentives Modeled

OFFERED TO EVERYONE

Assistance: Energy Efficiency Funds

Agency: MA DPU: Mass Save
Assistance:

- No Cost energy audit, air sealing and LEDs.
- Rebates for heating and cooling appliances.
- Rebate for 75% of insulation cost.
- Rebates for lighting and appliances.

Eligibility Criteria:

- 1-4-unit family home.
- If more than one unit in building parcitipates, than up to 90% rebate on insulation.

Assistance: Lead Abatement Funds

Agency: MA Department of Revenue
Assistance: $1,500 tax credit for lead abatement
Eligibility Criteria:

- 1-4-unit family home.
- Lead Abatement approved

Assistance: Energy Efficiency 0% Loans

Agency: MA DPU: Mass Save
Assistance:

- 0% loan up to $25,000 for a single family household to finance heating system replacement, water heaters, central air conditioning and heat pumps, and/or insulation & replacement windows.
- 0% loan for financing up to 50,000 for 2-4 dwelling units.

Eligibility Criteria: 1-4-unit family home.

Assistance: Historic Building Funds

Agency: MA Historic Rehabilitation Tax Credit
Assistance: Tax Credit for 20% of the cost of certified rehabilitation expenditures
Eligibility Criteria:
Income producing properties in compliance with the preservation toolkit

Assistance: Solar Funds

Agency: MA DOER
Assistance: Tax Credit for15% of system cost up to a maximum of $1,000.
Eligibility Criteria:
Eligible technology: Solar Water Heat, Solar Space Heat, Solar Photovoltaics, Wind (All), Wind (Small)

Assistance: Solar Funds

Agency: U.S. Internal Revenue Service
Assistance: Tax Credit for 30% of system cost.
Eligibility Criteria:
Eligible technology: Solar water heating property must be certified by SRCC or a comparable entity endorsed by the state where the system is installed. At least half the energy used to heat the dwelling's water must be from solar.

Assistance: Solar Funds

Agency: MA Department of Revenue
Assistance: 100% tax exemption for 20 years.
Eligibility Criteria:
Eligible technology: Solar Water Heat, Solar Space Heat, Solar Thermal Electric, Solar Photovoltaics, Wind (All), Hydroelectric, Wind (Small).

Assistance: Solar Funds

Agency: U.S. Internal Revenue Service
Assistance: 100% tax exemption.
Eligibility Criteria:
Eligible technology: Solar Water Heat, Solar Space Heat, Solar Photovoltaics, Wind (All), Wind (Small)

NEED BASED ASSISTANCE :
INCOME

Assistance: Energy Effeciency Funds

Agency: MA DPU: Mass Save

Assistance:

- Installation of instant energy savings products such as energy efficient LED light bulbs, advanced power strips, faucet aerators, low-flow showerheads, and more.
- Evaluation of appliances to determine if it is inefficient and eligible for a no-cost replacement with an energy efficient model.
- No-cost replacement of an existing boiler or furnace if the existing heating system is determined to be inefficient and eligible for replacement.
- Weatherization upgrades at no-cost including additional attic, wall, and basement insulation, as well as sealing drafts.

Eligibility Criteria: Mass Save Income Eligible residents (appendix A)

Assistance: Home Improvement 0% Loan

Agency: Boston DND

Assistance: Home Improvement 0% interest deferred loan up to $20,000.

Eligibility Criteria:

- owner occupied
- 1-4 units
- 120% of Area average income
- Additional $10,000 for triple-deckers.
- Homeowners earning between 120-135% AMI are required to provide $1:$1 matching funds.

INCOME + AGE

Assistance: Heating System Funds

Agency: Boston DND

Assistance: $3,500 grant and a 0% interest deferred loan for the balance.

Eligibility Criteria:

- owner occupied
- 1-4 units
- 80% of Area average income
- Age 60+
- Age 62+ entitled for additional 0% interest deferred home repairmen loan.

Assistance: Lead Abatement 0% Loan

Agency: Boston DND

Assistance: forgivable loans of up to $8,500 for each unit

Eligibility Criteria:

- owner occupied
- 1-4 units
- 80% of Area average income
- child 6-year-old or under
- If not owner then: at least 50% of the building's residents are low/moderate income, with remaining units occupied by families with an income at 80% or below of CDBG Moderate Income.

INCOME + HAZARD MITIGATION

Assistance: Barrier Mitigation Funds

Agency: MA DPU: Mass Save

Assistance: Barrier mitigation grant

- Knob and Tube Wiring- up to $7000
- Vermiculite- up to $7000
- Asbestos- up to $4000

Eligibility Criteria: Mass Save Enhanced residential program (appendix A)

Assistance: Lead Abatement Loan

Agency: MA Housing Finance Agency

Assistance: 0$ loan not due until the sale, transfer or refinancing of the property.

Maximum amounts:

- Single-family $30,000
- 2-family $35,000
- 3-family $40,000
- 4-family $45,000

Eligibility Criteria:

- 1-4 units
- Lead Abatement approved
- Income Eligible owner-occupants can get 0% deferred payment loans.

Appendix C: Eligibility to Goverment Incentives

Boston DND: INCOME ELIGIBILITY LIMITS

Adapted from the US Department of Housing & Urban Development (HUD)

80% Income Eligibility Requirements CDBG Moderate Income for Senior Home Repair & Lead Safe Boston:

- One-person household: $56,800
- Two-person household: $64,900
- Three-person household: $73,000
- Four-person household: $81,100
- Five-person household: $87,600
- Six-person household: $94,100

120% Income Eligibility Requirements for HomeWorks HELP & 3D HELP:

- One-person household: $ 90,550
- Two-person household: $103,500
- Three-person household: $116,400
- Four-person household: $129,350
- Five-person household: $139,700
- Six-person household: $150,050

120-135% Income Eligibility Requirements HomeWorks HELP & 3D HELP ($1:$1 Matching Funds Required):

- One-person household: $ 90,550-$101,850
- Two-person household: $103,500-$116,400
- Three-person household: $116,400-$131,000
- Four-person household: $129,350-$145,550
- Five-person household: $139,700-$157,150
- Six-person household: $150,050-$168,800

Mass Save – Low Income Criteria

Number of Household Members	Income Eligible Program Annual Household Income	Enhanced Residential Program Annual Household Income
1	Up to $35,510	$35,510.29- $47,347.00
2	Up to $46,437	$46,436.53- $61,915.00
3	Up to $57,363	$57,362.77- $76,484.00
4	Up to $68,289	$68,289.01- $91,052.00
5	Up to $79,215	$79,215.25- $105,620.00
6	Up to $90,141	$90,141.49- $120,189.00
7	Up to $92,190	$92,190.16- $122,920.00

Appendix D: Cost Estimates

Barrier abatement: $10 per sqft ($107 per sqm).
Energy Efficiency Measures:

Attic Insulation =$13.5 per sqm of attic floor area
Basement Insulation = $45 per sqm of basement floor area.
Walls Insulation =$22 per sqm of wall area.
Window Insulation =$110 per sqm of window area.
HVAC system upgrade = $70 per sqm of total building floor area.

Equipment upgrade to energy star or better appliances: $2500 per housing unit. Breakdown:

- Refrigerator- $500.
- Washing machine- $700.
- Dryer- $800.
- Dishwasher- $500.
- Oven- $350.

Solar panels
$3.05 per installed watt.

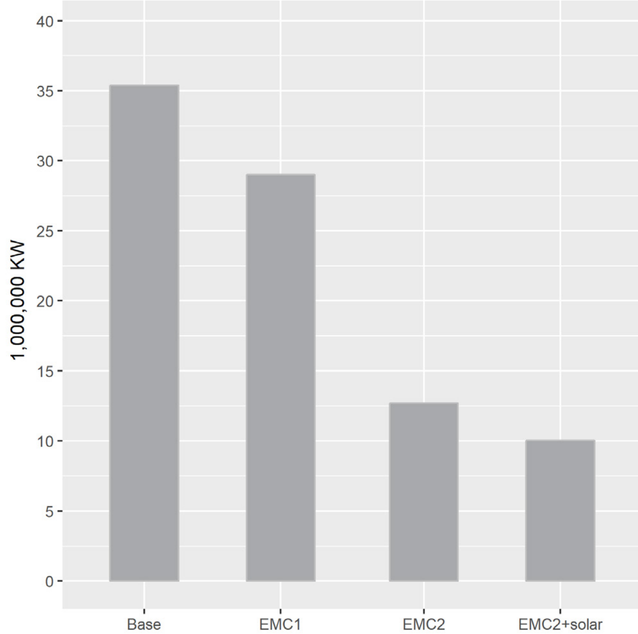
Appendix E: Data Analysis & Visualization Scripts

Scripts will be available on this site after publication

https://github.com/yaelnidam

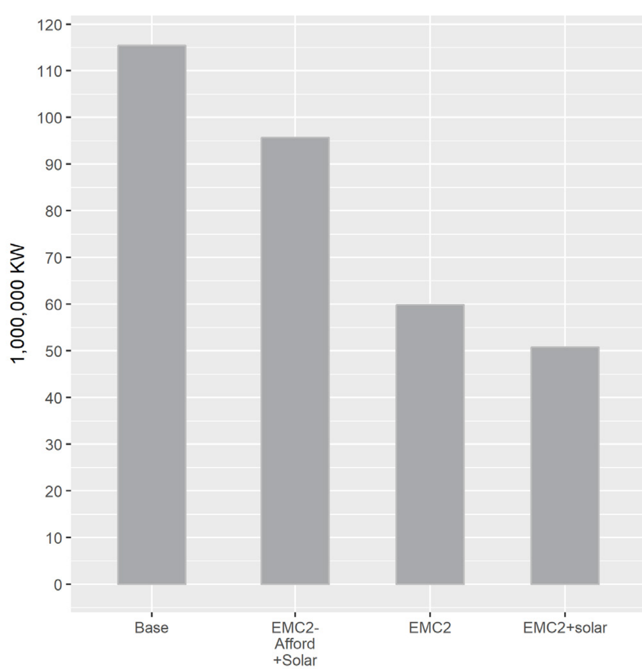
Appendix F: Energy Consumption for All Building Types in Neighborhoods

Dudley Triangle Total Annual Neighborhood Energy Consumption (1,000,000 KWh) by Scenario



Total Neighborhood Energy Consumption encompassing all buildings, calculated by Bemis and Irani (2016).

South End Total Annual Neighborhood Energy Consumption (1,000,000 KWh) by Scenario



Total Neighborhood Energy Consumption encompassing all buildings, calculated by Bemis and Irani (2016).

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