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The Transition to Clean Energy and the Role of Building Envelope Efficiency

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ABSTRACT

The electrification of building systems and the improvement of their envelopes must work in tandem to achieve a truly energy efficient and sustainable outcome. Many jurisdictions, including Boston, MA, and Acton, MA, have already released climate action plans, detailing many steps that can be taken to decarbonize. These plans have many specific strategies when it comes to buildings, from incentivizing building improvements on private property to retrofitting municipal buildings. Building electrification includes many aspects, from the electrification of household appliances like stoves to the conversion of traditional heating and cooling systems to heat pumps; an electrification roadmap by Acton lists many specifics when it comes to the electrification of its municipal buildings. The improvement of envelope, encompassing aspects of a building such as its insulation, air sealing, windows, moisture control, and ventilation system, is an aspect of sustainability that is arguably more important than the pure electrification of systems. Envelope improvements will improve heat pump efficiency at colder temperatures, and will result in significant energy use and cost reductions.

Introduction

While it seems to be the most pressing concern, moving towards a more sustainable future requires not only the electrification of fossil fuel systems, but also increased energy efficiency. This paper focuses on this aspect of sustainability, specifically the energy efficiency of buildings with emphasis on its importance in colder climates such as in Massachusetts. It initially outlines some parts of the climate action plans of Boston, MA, and Acton, MA, and then examines the electrification of buildings and the electrification roadmap Acton has published for its municipal buildings. It then lays out various measures that can be taken to improve a building's energy efficiency.

Climate Action Plan Examples

Many municipalities have started creating climate action plans laying out various strategies, regulations, and incentives intended to decrease greenhouse gas emissions and transition to more sustainable energy sources. Two of these plans, both from municipalities in Massachusetts, are described in this paper.

Boston, MA, released an update to its climate action plan in 2019. The city's target is to reduce community-wide carbon emissions by 50% by 2030, with the goal of 100% reduction by 2050 (relative to 2005 emission levels). Additionally, the city plans to reduce municipal carbon emissions by 60% by 2030, also with the goal of 100% reduction by 2050. Figure 1 shows Boston's greenhouse gas emissions from 2005-2017 as well as projections of needed emissions reductions to meet certain goals.

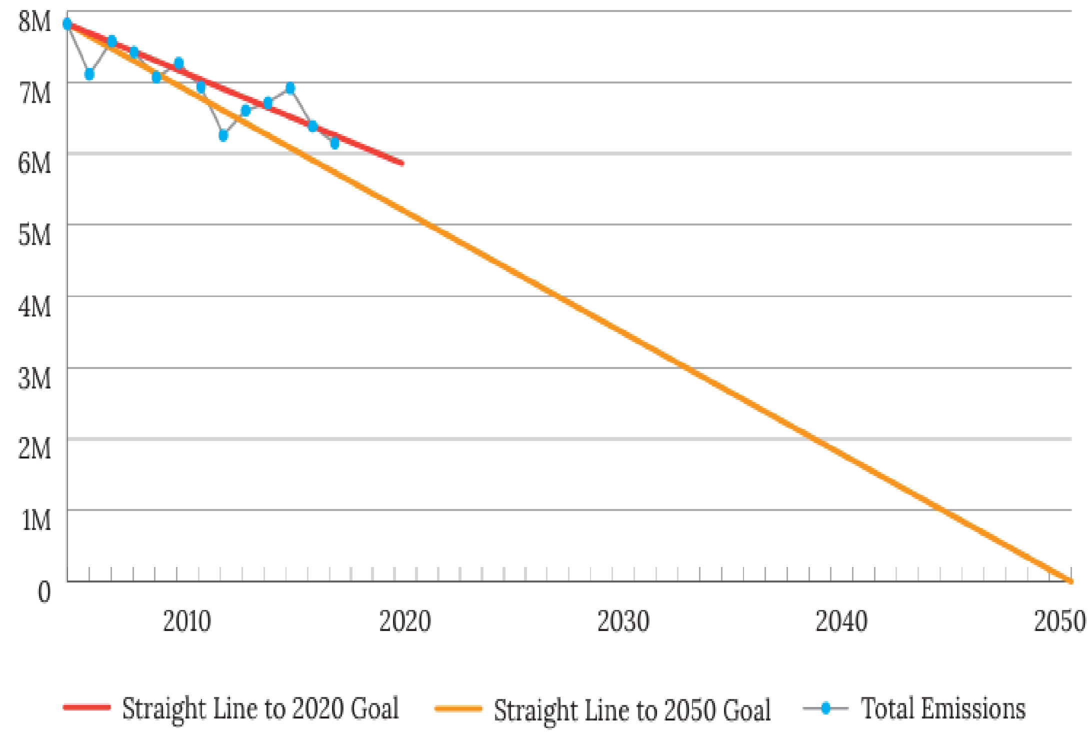

Figure 1. Boston greenhouse gas emissions (2005-2017) and goals ("City of Boston 2019 Climate Action Plan")

In 2017, Boston emitted 4.3 MMT CO_2e (million metric tonnes of carbon dioxide equivalent): 52% of that came from commercial, industrial, or large residential sources, 29% came from transportation, 19% came from small residential, and the rest came from smaller sources like fugitive emissions or wastewater treatment ("City of Boston 2019 Climate Action Plan"). To decrease the amount of emissions it outputs, Boston has developed a plan containing various strategies sorted by category: buildings, transportation, and energy supply. In line with the focus of the paper, the building aspects of the plan will be focused on more than the transportation and energy aspects.

Boston has more than 86,000 buildings, and an estimated 80% of these buildings will have to undergo deep energy retrofits and electrification by 2050. As defined by the plan, a deep energy retrofit is a retrofit that achieves a 50% or more reduction in energy use ("City of Boston 2019 Climate Action Plan"). This can include upgrading lighting systems and appliances, upgrading HVAC and plumbing, as well as envelope measures such as insulation, air sealing, and window replacement which will be presented in greater detail later in this paper.

Part of this effort will be the usage of performance standards for large buildings. According to the climate action plan, the 2,200 largest buildings in Boston account for 34% of total floorspace in the city but half of the city's total emissions ("City of Boston 2019 Climate Action Plan"). These performance standards will have carbon targets that decrease over time and different standards for different types of buildings. The city will also make greater use of the reporting requirement of its Building Emissions Reduction and Disclosure Ordinance, mandating certain buildings report on their energy use and performance.

In addition to regulations on private property, the city itself will focus on the energy efficiency of its own municipal buildings. Newly constructed municipal buildings must make use of little to no fossil fuels as well as be highly energy efficient. These new constructions will follow a tiered Zero Net Carbon (ZNC) standard. The four tiers are ZNC-onsite, ZNC-offsite, ZNC-ready, and ZNC-convertible. These same ZNC standards will be applied to stronger green building zoning requirements as well as for any city-funded affordable housing

("City of Boston 2019 Climate Action Plan"). The city will also expand its workforce development programs for positions ranging from facilities management to construction trades.

In the transportation sector, Boston output 1.8 MMT of CO_2e in 2017. 65% of that was a result of passenger vehicles, and 75% of it came from travel in and out of the Boston metropolitan area ("City of Boston 2019 Climate Action Plan"). Strategies laid out in the plan include increased advocacy for priority transit projects, the improvement and expansion of walking and biking options, and the encouragement of public transit usage versus driving alone. The city will also encourage the development of zero-emission vehicles, support more electric vehicle charging infrastructure, and transition current municipal vehicles to zero- and low-emission alternatives.

Boston intends to achieve 100% clean energy in its energy supply by 2050 by making use of its Community Choice Energy aggregation program, deploying carbon-neutral microgrids, and supporting state decarbonization policies and programs. Other miscellaneous strategies include the reduction of waste and consumption-based emissions and investment in companies with strong environmental, social, and governance practices.

Acton, MA, is a relatively small town, containing around 24,000 residents in 2020 compared to Boston's 675,000 residents (U.S. Census Bureau). Nonetheless, the town published a robust climate action plan in 2022 that includes many of the same strategies as its Boston equivalent. The plan is divided into six categories: buildings and housing, energy, mobility, nature-based solutions, solid waste, and resilience.

Residential energy comprises 22% of total community-wide emissions and commercial energy comprises 16% of them ("ActOn Climate: The Road to a Resilient Net Zero Future"). Some strategies included in the building and housing section of the plan are supporting residents and businesses during the transition to clean heating and energy efficiency (possibly through Mass Save, a state-wide financing program), expanding outreach with the Property Assessed Clean Energy (PACE) program (another financing program), and implementing geothermal micro-districts.

Acton will also use zoning and planning to increase clean energy usage and sustainability by allowing more multifamily housing choices. The town will also investigate the possibility of building more affordable housing and mixed-use development near public transit options and business centers, and exclude the use of fossil fuels in new construction and major building retrofits.

The town itself will contribute to the goal of net zero by using a net zero standard for new municipal buildings and major retrofits. Details on the electrification of various municipal buildings are provided in Acton's electrification roadmap, which is described in detail later on in this paper. Acton will also advocate for policy changes at the state and federal level such as further incentives for electric heating and cooling, low-cost financing options, a net zero building code, and expanded programs to track and fix gas leaks.

In terms of energy supply, the town aims to provide 100% clean energy by 2030 through its community aggregation program Acton Power Choice, as well as expanding access to local clean energy, mainly solar. All municipal buildings will be powered by 100% clean energy by 2030, and the town will advocate for policy changes and investments on the state level to accelerate electrification.

Half of community-wide emissions are due to on-road transportation. Acton's climate action plan's mobility section includes strategies such as the promotion of electric vehicle adoption, the electrification of school buses and town vehicles, the expansion of electric vehicle charging infrastructure, the expansion of walking and biking options, and the advocacy of the electrification of other transportation options such as the Massachusetts Bay Transportation Authority's Commuter Rail.

Unlike Boston's climate action plan, Acton has made nature-based solutions a big part of its decolonization efforts, most likely due to Acton's more suburban nature and greater abundance of undeveloped land and green spaces. Acton will make the protection of existing green spaces a priority and support sustainable agriculture. The town will also electrify municipal landscaping equipment and encourage residents to do the same; it will also advocate for policies for nature-based solutions, an example being the incorporation of projections and impacts of climate change into the Massachusetts Wetlands Protection Act and Acton's town wetland bylaws.

To curb solid waste, the town will expand waste reduction services, increase its waste diversion rate, and support zero waste initiatives. The town's nature-based solutions help its effort to increase resilience to future climate change; it will also use the most recent climate change data when planning resilience efforts and update its bylaws and procedures.

Building Electrification and Energy Efficient Systems

Part of the effort of decarbonization is the electrification of existing buildings. In 2019, around 13% of all greenhouse gas emissions in the United States were a result of residential or commercial buildings ("Electrification 101"). Building electrification consists of converting systems that traditionally use fossil fuels into ones that use electricity, such as home appliances like stovetops and dryers, as well as heating and cooling systems.

Many home appliances can be upgraded to electric equivalents. For example, while electric clothes dryers are more common than gas dryers, one can upgrade to an ENERGY STAR certified electric dryer. Also available are heat pump dryers, which use 28% less energy than standard dryers ("Heat Pump Dryer"). Heat pump dryers use evaporators to remove moisture instead of removing humid air through a dryer vent.

Another appliance that can be upgraded is the stovetop in the kitchen. Instead of using a gas stove, one can use an electric or an induction stove. Electric stoves heat up metal coils that transfer heat to the surface of the stovetop, which then transfers to cookware. Induction stoves use magnetic currents to directly heat any ferromagnetic cookware, bypassing the need to heat a stovetop surface. Induction stoves are more efficient compared to other heating systems, meaning less energy is needed when using them; around 90% of energy generated by induction stoves is transferred to cookware, while a comparable gas stove transfers only 38% of energy generated ("Induction vs. Electric Cooktops: Which Is Right for You in 2021?"). A diagram of an induction stove system is shown in Figure 2.

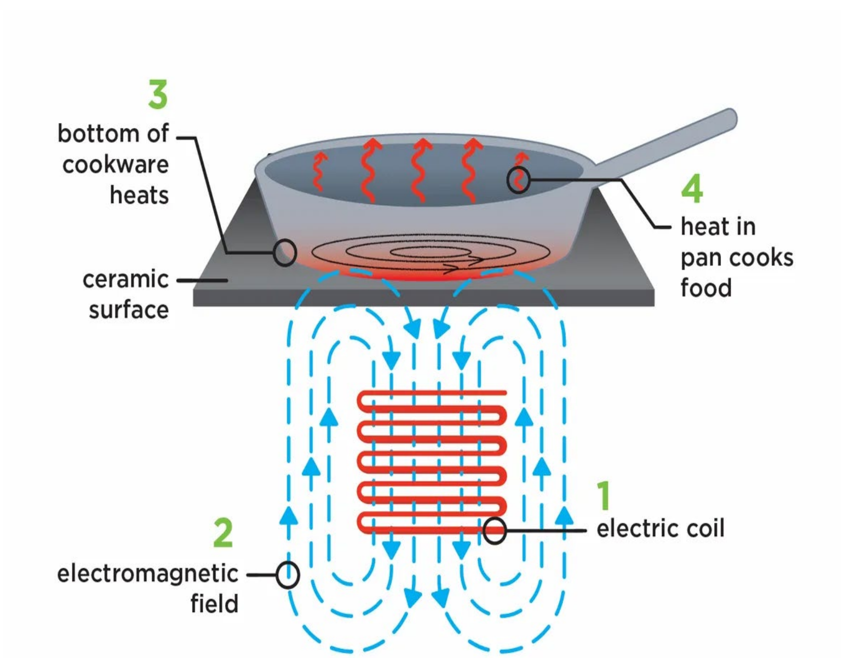

Figure 2. Induction stove ("How Do Induction Stoves Actually Work?")

Traditional heating and cooling systems can be replaced with heat pumps. Heat pumps work by moving heat, either from outside to inside to heat a building, or from inside to outside to cool it, using only electricity. There are two main types of heat pumps: air source and ground source.

Air source heat pumps are the most common type of heat pump, transferring heat between a building and the air outside of it. During the heating season, refrigerant inside the heat pump takes heat from the air and turns into a gas, which then condenses back into a liquid to release that heat into the building. To cool a building, a reversing valve can be used to change the direction of the refrigerant, moving heat outside. A diagram of an air source heat pump is provided in Figure 3.

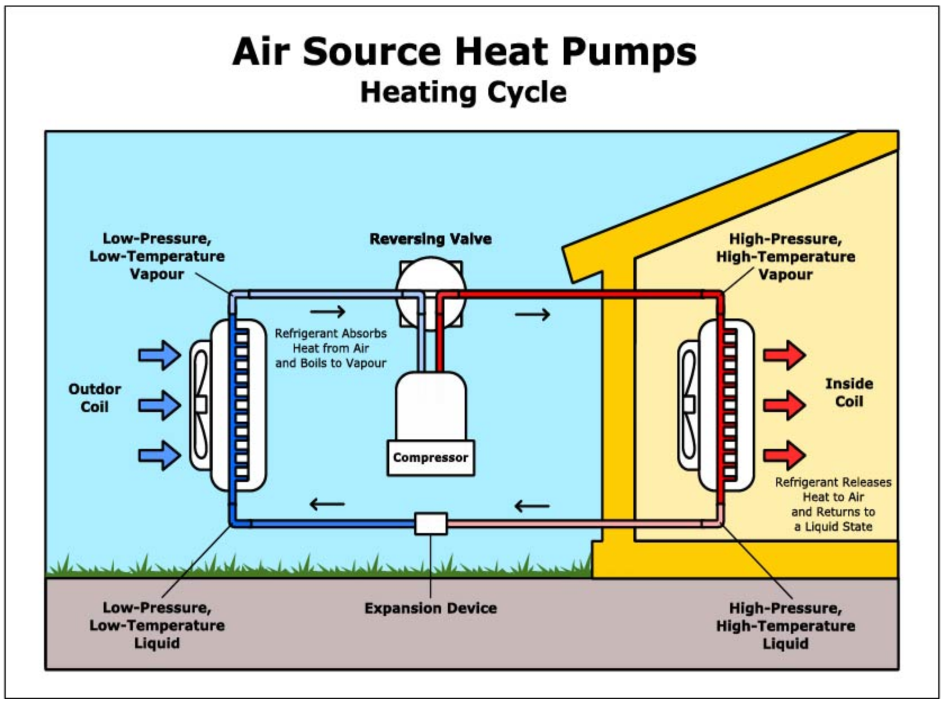

Figure 3. Air source heat pump ("Air-Source Heat Pumps")

Ground source heat pumps work similarly, transferring heat from either the ground or a water source. Due to the need to build infrastructure underground when converting to a ground source heat pump, it is more invasive to install than an air source heat pump as well as more expensive. A diagram of a ground source heat pump is provided in Figure 4.

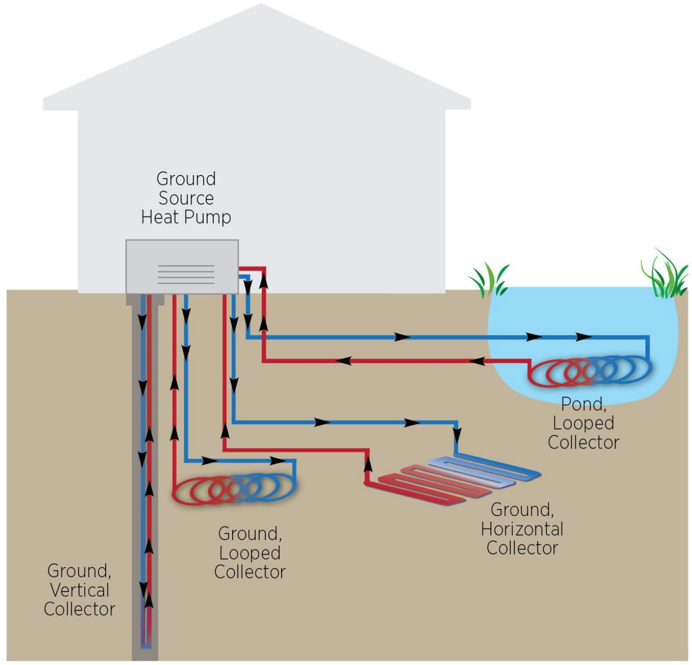

Figure 4. Ground source heat pump ("Ground-Source Heat Pumps")

An advantage of ground source heat pumps is that they are more suited for colder climates since the ground has a constant temperature unlike air. This does not mean air source heat pumps cannot function in colder climates; modern cold-climate air source heat pumps are capable of providing comfortable heating in temperatures as low as -15°F ("Do Heat Pumps Really Work in Cold Climates?"). Regardless, since air source heat pumps are the most common heat pump, having an efficient building envelope and having as little heat transfer as possible is exceedingly important when transitioning to electric systems, particularly in colder climates.

Heat pumps can also be used as a water heating system (see fig. 5). Compared to traditional water heaters, heat pump water heaters can be as much as two or three times more energy efficient ("Heat Pump Water Heaters").

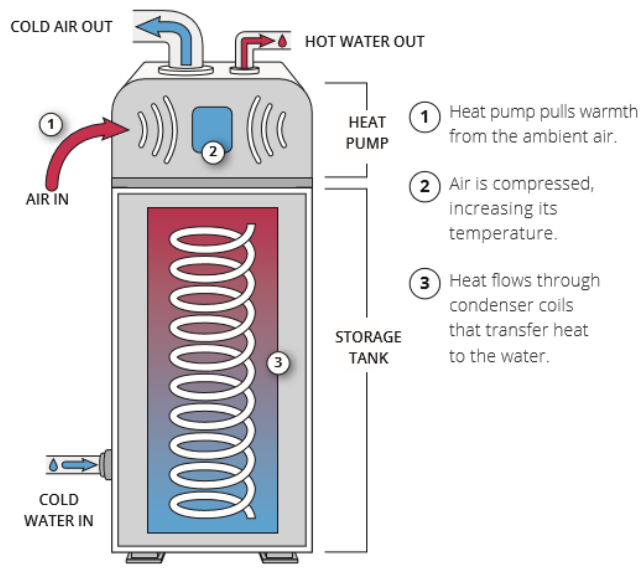

Figure 5. Heat pump water heater ("What Are Heat Pump Water Heaters?")

Buildings can also use more energy efficient systems, like energy efficient lighting systems. This can include using LED lights instead of incandescent bulbs, usually ones with an ENERGY STAR certification. Buildings can also use timers to turn off lights when they are not being used and dimmers to lower the brightness, conserving energy when it is not needed.

Acton Electrification Roadmap

The Town of Acton published a study on electrification in 2022, detailing retrofits that can be made to many town and school buildings within the town. These buildings are split into two categories: Town of Acton and Acton-Boxborough Regional School District (ABRSD). Town of Acton buildings include the Acton Town Hall, Acton Memorial Library, and Public Safety Facility. ABRSD buildings include the Acton-Boxborough Regional High School, R.J. Grey Junior High School, Parker Damon Building, and Administration Building. The roadmap assumes the Town of Acton buildings will be electrified by 2030 (in line with a 2020 Acton Climate Emergency Declaration), with the ABRSD buildings being electrified by 2050.

The roadmap details existing systems each building has. Every building besides the town hall, which is heated by Fan Coil Units, is heated by natural gas boilers connected to hydronic heating systems (systems that use water to disperse heat). Many of the buildings also have Rooftop Units and Air Handling Units to provide heating, cooling, and ventilation. Every building besides the Administration Building has either a backup natural gas generator or diesel generator.

The roadmap also includes a breakdown of Business as Usual (BAU) forecasts for each building. For example, the high school, if run as it currently is, is forecasted to have a total annual heating and cooling cost of $179,295, an annual maintenance cost $53,900, and an annual emissions rate of 687 MT of CO_2e. The annual estimated maintenance cost for all Town of Acton buildings is $77,415, while the comparable cost for ABRSD buildings is $98,000 ("Electrification Roadmap: Town of Acton and Acton-Boxborough Regional School District").

If all buildings in contained within the study replace their existing systems with equivalent systems, refraining from upgrading any of them to more sustainable alternatives, than the capital expenditures would be $1,417,045 for Town of Acton buildings, and $12,307,589 for ABRSD buildings. These costs would be spread out over an approximately 30 year period, from the time of the study to 2051 ("Electrification Roadmap: Town of Acton and Acton-Boxborough Regional School District").

The roadmap includes many electrification options the Town of Acton can use when retrofitting its existing buildings. The first of these options is the use of low-temperature hot water (LTHW) instead of high-temperature hot water (HTHW). A LTHW system has less heat loss, lower costs, improved safety, and can be used for more electrified energy sources (such as heat pumps) than a HTHW system.

Air source heat pumps are the second option recommended by the roadmap. As stated before, they work better with LTHW systems than HTHW systems, and, while less efficient than ground source heat pumps, are less expensive to install and still work well.

The roadmap also recommends the use of onsite solar to both power the buildings and heat water. Onsite solar would include the installation of photovoltaic (PV) arrays on roofs and parking canopies. The high school and junior high school both already have PV arrays installed, and there are plans to install a PV array at the Public Safety Facility. In addition, onsite PV arrays are being evaluated for all other buildings included within this study, and there are continued plans to install PV arrays through power purchase agreements.
Also included in potential retrofits are envelope improvements and heat recovery ventilation systems, improvements discussed in detail later on in this paper.

Specific electrification measures for each building are listed in the roadmap. If these actions are taken, the Town of Acton buildings are each estimated to have an emissions reduction of around 64%, with each ABRSD building having an emissions reduction of 100%. Each building will have utility costs go up, with the smallest increase being 6.3% for the library and the largest being 52% for the junior high, but the overall energy use relative to BAU for each building will decrease 54-69% depending on the building ("Electrification Roadmap: Town of Acton and Acton-Boxborough Regional School District").

The estimated conversion cost of the buildings, at cost of $35 per square foot, is $3,445,260 for all Town of Acton buildings, and $24,745,000 for all ABRSD buildings ("Electrification Roadmap: Town of Acton and Acton-Boxborough Regional School District").

Building Envelope Efficiency

Improving building envelopes to increase energy efficiency is a crucial step when it comes to moving towards a more sustainable future; as already mentioned, this will be especially true when it comes to the installation of heat pumps in colder climates. Envelope improvements include many different techniques and strategies which all work in tandem to form an energy efficient building. Various parts of a building's envelope include the walls, windows, doors, and roof. Some methods of improving an envelope include adding insulation, air sealing, updating or replacing windows, and moisture control. All these measures can be used on both new construction and existing buildings; this paper focuses specifically on the renovation of existing buildings. Some aspects of a building's envelope are shown in Figure 6.

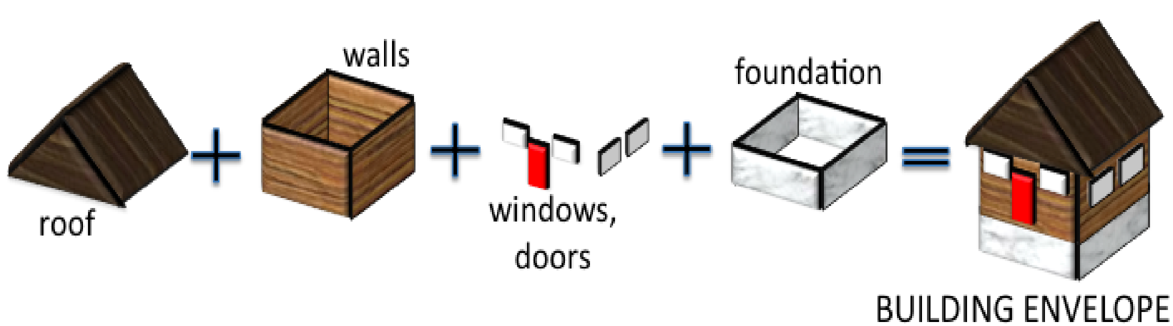

Figure 6. Components of building envelope ("Building Envelope")

Insulation works by reducing the flow of heat in the home. Heat flows towards cold areas, so from inside to outside in the winter and outside to inside in the summer. The thermal effectiveness of insulation is measured by its R-value; the higher the R-value, the better the insulation. Improvements to insulation can be one of the easiest and least invasive improvements one can make. The United States is divided into eight climate zones, with the Department of Energy having recommended R-values for each (see fig. 7; "Insulation"). For example, an attic in Zone 1 is recommended to have an insulation of R30-R49, while one in Zone 5 is recommended to have an insulation of R60.

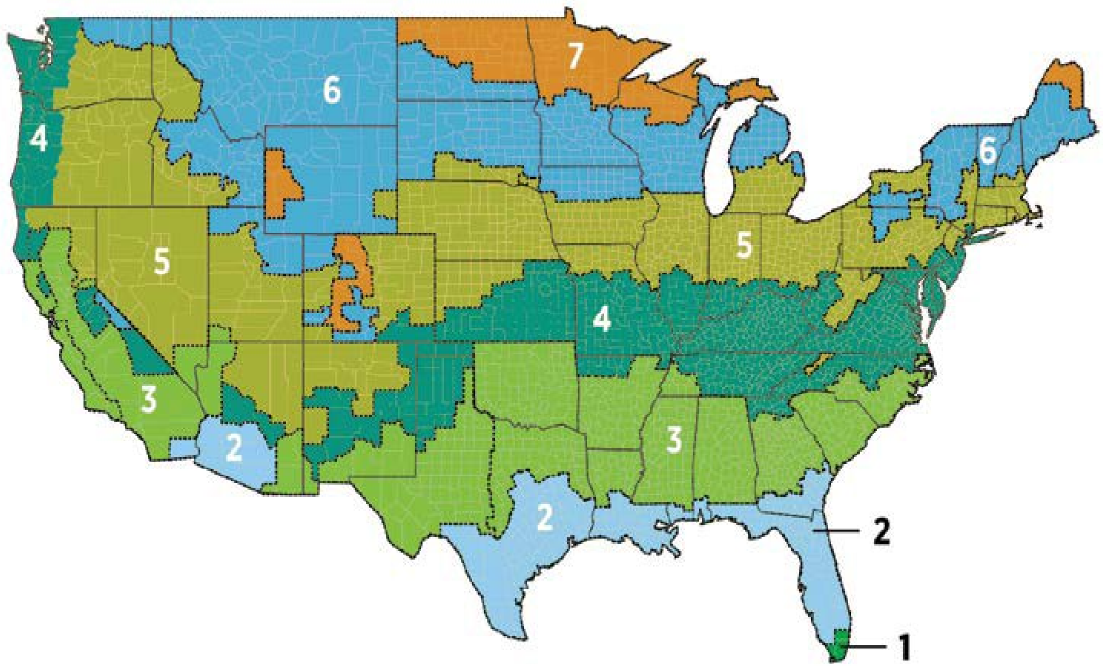

Figure 7. Climate zones ("Insulation")

Some improvements include adding insulation in attics, basements, walls, and rim joists, typically with materials such as fiberglass, spray foam, and polystyrene. Rim joists, the outside frame to the joists that run laterally below a home's floor, are especially susceptible to heat transfer since they are the barrier between the outside and inside (see fig. 8). This makes it particularly important that rim joists are properly insulated. Adding insulation, especially when it comes to attics, can be one of the easiest non-invasive improvements one can make. Adding insulation to walls and rim joists are more substantial improvements that may require their removal and replacement.

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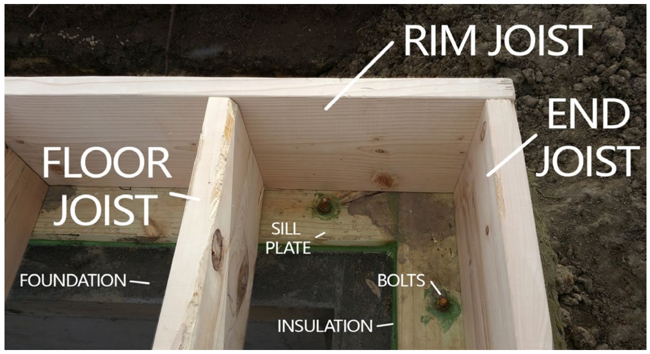

Figure 8. Rim joist (“What Is a Rim Joist?”)

Air leakage is the uncontrollable loss of heat and ventilation. It can lead to energy waste and poorer air quality, so sealing these leaks will result in increased energy efficiency and comfort. According to the American Council for an Energy-Efficient Economy, an “average American home is two to four times leakier than a new home built to code”, and by air sealing a home’s envelope, air leakage can be reduced by 25-30% (“Empowering Electrification through Building Envelope Improvements”). Air sealing measures can be fairly easy and non-invasive, and may include strategies such as caulking and weatherstripping around doors and windows. Just like with insulation, the rim joist is also an important area that has to be air sealed. Not only being an area of great heat loss, the rim joist is also an area that suffers from serious air leakage and must be properly sealed.

Energy efficient windows are another important part of building envelope. According to the Department of Energy, 25-30% of all residential heating and cooling use is due to heat transfer through windows. When it comes to improving window efficiency, one can either update them or replace them entirely. Updating a window is much less invasive when compared to replacing a window.

Updating windows may include measures like air sealing or window attachments. An example of a window attachment is solar control film, which can be applied to any window to block heat from the sun, making it most useful in areas with longer cooling seasons. Low-e storm windows or panels are also a good option. Low-e refers to the emissivity of an object, or how well an object radiates energy. The lower the emissivity, the better the object is at radiating energy. As a result, low-e storm windows are 35% better at reflecting heat than their clear glass counterparts. Low-e storm windows can also reduce air leakage in a home by 10% or more (“Storm Windows”).

Beyond updating windows, they can also just be outright replaced by high efficiency alternatives, most likely ones that are ENERGY STAR certified. There are many types of windows, and the best one for any particular building will be dependent on its location and climate. Windows with multiple panes of glass and space in between the layers are better at insulation than single pane windows (see fig. 9). In a colder climate like that of Massachusetts, one may even consider gas filled windows, which are multi pane windows with gasses such as argon and krypton in between each pane. These are even better at preventing heat loss.

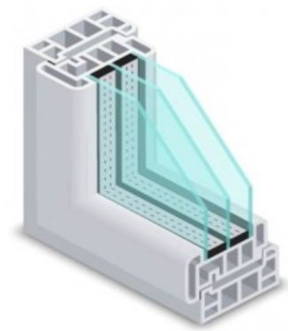

Figure 9. Multi pane window ("Window Types and Technologies")

Something that also should be considered when improving a building's envelope is moisture control. The choice of materials, and construction methods, need to effectively manage vapor in wall systems. The site the building is on should be graded to allow surface water to drain away from its foundation with the exterior allowing for drainage as well. Additionally, groundwater should be kept away from the foundation of the building.

The Passive House Standard is a standard for building energy efficiency. The standard's requirement for an energy efficient house is one with a building envelope allowing a maximum of 0.6 air changes per hour at 50 Pascals pressure. This standard pertains only to a building's airtightness without consideration of air changes as a result of a dedicated ventilation system. This would be tested after the installation of the system, typically through a blower door test. A blower door test involves a fan pulling air out a building to lower pressure (or, if that is not possible, blowing air into a building to increase pressure) to find any unsealed cracks or openings through which air is flowing.

When it comes to ventilation, buildings have been traditionally ventilated through natural ventilation. Natural ventilation is unpredictable and uncontrollable as it relies on air leaking through cracks in a building's envelope, which can cause condensation and water damage. Furthermore, depending on the weather, natural ventilation may not dilute or remove pollutants in the air enough, and may also make a building uncomfortable due to drafts. Since the goal is to seal buildings to achieve greater energy efficiency, natural ventilation is obviously not an option. Thus, energy efficient homes must have a robust ventilation system that works together with their envelopes.

The ventilation system installed should have control over both supply air and exhaust air and be some type of mechanical energy recovery system. Heat recovery is the process in which leftover thermal energy from exhaust air is recovered and transferred into supply to be reused in the building (see fig. 10). These systems improve the energy efficiency of a building, but they can only be effective if the building has been sufficiently sealed. Heat recovery ventilation systems are a requirement under the Passive House Standard.

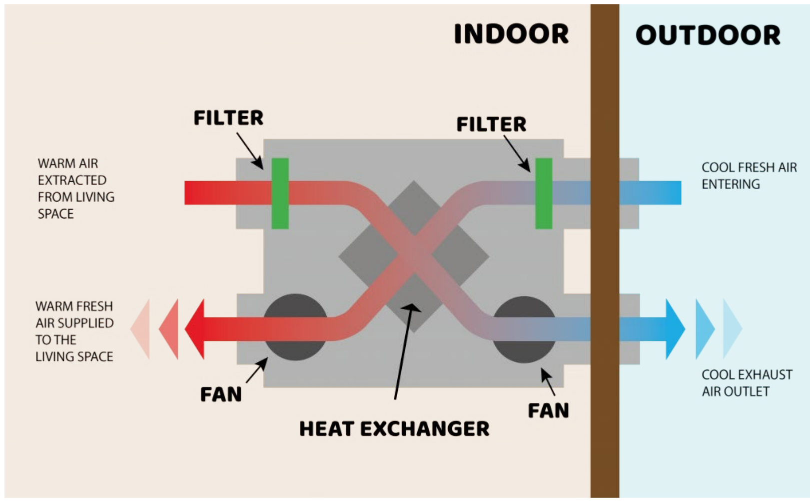

Figure 10. Heat recovery system ("Heat Recovery - What Is It and How Does It Work?")

Improving a building's envelope has a variety of benefits ranging from energy savings to cost savings. According to the American Council for an Energy-Efficient Economy, modest envelope measures like air sealing and insulation can reduce energy usage by 12-18%, while more substantial improvements can reduce energy usage by an average of 33%. Envelope improvements can deliver some of the greatest benefits in colder climates. In Massachusetts, when it comes to single-family homes, modest improvements reduced energy usage by 18%, while substantial improvements reduced usage by 38% ("Empowering Electrification through Building Envelope Improvements").

Building electrification, while necessary for a sustainable future, will increase peak electric loads. A better envelope in electrified buildings can reduce peak electric loads by 7-10%. Due to electrification in single-family homes in Massachusetts, peak electric loads are expected to increase by 73%; envelope improvements could reduce that by 23-42% ("Empowering Electrification through Building Envelope Improvements").

Most households can be expected to save $500-800 annually. In an electrified home in Massachusetts, one can be expected to save $672 annually on heating costs and $85 annually on cooling costs. Envelope improvements will also produce significant reductions in greenhouse gas emissions; in Minneapolis, 75% of potential building decarbonization comes from weatherization and space heating electrification. A weatherized electrified home in Massachusetts, in only its first year, can reduce its space heating emissions from 3.0 tons of CO_2e to 1.8 tons of CO_2e. Figure 11 shows the difference in utility costs that arise when a building that has been electrified is weatherized or not ("Empowering Electrification through Building Envelope Improvements").

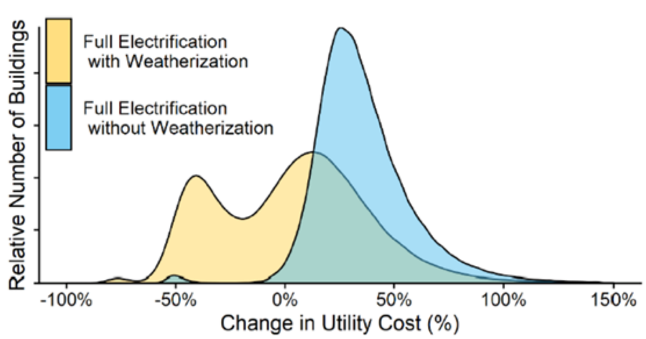

Figure 11. Change in utility costs from electrification with and without weatherization ("Empowering Electrification through Building Envelope Improvements")

Other benefits include higher indoor air quality, higher resilience to power outages (something that is especially pertinent in periods of extreme heat or cold), and enhanced grid interactivity.

Through all these changes and improvements to a building's envelope, the end goal is to not only make an energy efficient building, but also to make a comfortable one. If people using the building find it uncomfortable, they may use or maintain the building in a way that undercuts any intended improvements.

Conclusion

Building decarbonization and electrification is a difficult process, and there are many details that have to be considered when going through that process. Many factors, including cost, location, and climate have a considerable impact on what options are available. The improvement of building envelopes can make electrification more effective. An example brought up many times in this paper is the benefit of improved envelope on the use of heat pumps in colder climates. Not only will this make the overall process easier, but it will also reduce the cost of electrification, allowing it to be available to more people, especially those with less money. Electrification and building envelope improvements must be utilized together if we are to make substantial progress towards sustainability.

Suggestions for Further Research

Many governments, including Massachusetts with its Mass Save program, have financing measures intended to help alleviate cost concerns when it comes to electrification. A future paper could research how these programs, such as Mass Save and PACE, work, and compare different programs to see what is effective and what is not; these could include both state and federal programs. In the same vein, further research could be done on what regulations are in place when it comes to electrification, such as what standards are used for building energy efficiency.

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References

"ActOn Climate: The Road to a Resilient Net Zero Future." *Town of Acton,* July 2022, https://www.acton-ma.gov/DocumentCenter/View/8096/Climate-Action-Plan-Final.

"Air Sealing Your Home." *Department of Energy,* https://www.energy.gov/energysaver/air-sealing-your-home.

"Air-Source Heat Pumps." *Department of Energy,* https://www.energy.gov/energysaver/air-source-heat-pumps.

"Blower Door Tests." *Department of Energy,* https://www.energy.gov/energysaver/blower-door-tests.

"Building Envelope." *Energy Education,* University of Calgary, https://energyeducation.ca/encyclopedia/Building_envelope.

"City of Boston 2019 Climate Action Plan." *City of Boston,* https://www.boston.gov/sites/default/files/embed/file/2019-10/city_of_boston_2019_climate_action_plan_update_4.pdf.

"Do Heat Pumps Really Work in Cold Climates?" *NYS Clean Heat,* New York State Energy Research & Development Authority, https://cleanheat.ny.gov/heat-pumps-cold-climates-do-they-work/.

Dellinger, AJ. "Induction vs. Electric Cooktops: Which Is Right for You in 2021?" *CNET,* Apr. 21 2021, https://www.cnet.com/home/kitchen-and-household/induction-vs-electric-cooktops-which-is-right-for-you-in-2021/.

"Electrification Roadmap: Town of Acton and Acton-Boxborough Regional School District." *Town of Acton,* Salas O'Brien, July 20, 2022, https://www.acton-ma.gov/DocumentCenter/View/8089/Acton-Electrification-Roadmap-Final-Report-and-Appendices.

"Electrification 101." *Resources for the Future,* https://www.rff.org/publications/explainers/electrification-101/.

"Empowering Electrification through Building Envelope Improvements." *American Council for an Energy-Efficient Economy,* July 2023, https://www.aceee.org/sites/default/files/pdfs/empowering_electrification_through_building_envelope_improvements_-_encrypt.pdf.

"Energy Efficient Window Coverings." *Department of Energy,* https://www.energy.gov/energysaver/energy-efficient-window-coverings.

"Gas vs. Electric Dryers: Which is Best?" *Direct Energy,* https://www.directenergy.ca/learn/gas-vs-electric-dryers.

"Ground-Source Heat Pumps." *Building America Solution Center,* Department of Energy, https://basc.pnnl.gov/resource-guides/ground-source-heat-pumps.

"Heat Pump Dryer." *ENERGY STAR,* U.S. Environmental Protection Agency and U.S. Department of Energy, https://www.energystar.gov/products/heat_pump_dryer.

"Heat Pump Systems." *Department of Energy,* https://www.energy.gov/energysaver/heat-pump-systems.

"Heat Pump Water Heaters." *Department of Energy,* https://www.energy.gov/energysaver/heat-pump-water-heaters.

"How Do Induction Stoves Actually Work?" *Canary Media,* https://www.canarymedia.com/articles/electrification/how-do-induction-stoves-actually-work.

"How Low-e Glass Works." *Vitro Glass Education Center,* Vitro Architectural Glass, https://glassed.vitroglazings.com/topics/how-low-e-glass-works.

"Info-408: Critical Seal (Spray Foam at Rim Joist)." *Building Science,* Building Science Corporation, 17 Sep. 2009, https://buildingscience.com/documents/information-sheets/critical-seal-spray-foam-at-rim-joist.

"Insulation." *Department of Energy,* https://www.energy.gov/energysaver/insulation.

"Lighting Choices to Save You Money." *Department of Energy,* https://www.energy.gov/energysaver/lighting-choices-save-you-money.

"Passive House Certification Criteria." *International Passive House Association,* https://passivehouse-international.org/index.php?page_id=150.

Pettit, Betsy. "RR-1401: Design Challenges of the NIST Net Zero Energy Residential Test Facility." *Building Science,* Building Science Corporation, 18 Sep. 2014, https://buildingscience.com/documents/reports/rr-1401-design-challenges-nist-net-zero-energy-residential-test-facility/view.

"Sealing and Insulating Rim Joists." *InSoFast,* 5 Mar. 2016,

https://www.insofast.com/explore/sealing-and-insulating-rim-joists.html.
“Storm Windows.” *Department of Energy,* https://www.energy.gov/energysaver/storm-windows.
“Update or Replace Windows.” *Department of Energy,* https://www.energy.gov/energysaver/update-or-replace-windows.
U.S. Census Bureau. *Quick Facts,* https://www.census.gov/quickfacts/fact/table/bostoncitymassachusetts,actontownmiddlesexcountymassachusetts/POP645221.
“Ventilation.” *Department of Energy,* https://www.energy.gov/energysaver/ventilation.
“What Are Heat Pump Water Heaters?” *CleanBC Better Homes,* https://www.betterhomesbc.ca/products/what-are-heat-pump-water-heaters/.
“What Is a Rim Joist?” *Gambrick Construction,* https://gambrick.com/what-is-a-rim-joist/.
“Heat Recovery - What Is It and How Does It Work?” *Pure Ventilation,* https://www.pureventilation.com.au/heat-recovery/.
“Window Types and Technologies.” *Department of Energy,* https://www.energy.gov/energysaver/window-types-and-technologies.