Buildings Sector Report

A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study

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1 Executive Summary

The following technical report describes an analysis of sources of greenhouse gas (GHG) emissions from the commercial and residential building sectors, with the intention of providing insights into technological, market-based, and policy-driven opportunities and barriers for decarbonizing those sources. The work was conducted by a team of engineers and consultants at Arup, the Cadmus Group, and VEIC, working as part of the Massachusetts Executive Office of Energy and Environmental Affairs' (EEA's) 2050 Decarbonization Roadmap Study. This detailed analysis complements the high-level economy-wide analysis performed by Evolved Energy Research and published in the companion *Energy Pathways Report*.

On-site combustion of fossil fuels in the residential and commercial buildings subsectors was responsible for 27% of statewide GHG emissions in the Commonwealth in 2017, the latest year with official emissions data. Emissions in these subsectors have generally trended downward since 1990 despite weather fluctuations year to year. This is despite a 16% growth in the Commonwealth's building stock since 1990. With over 2 million individual buildings in Massachusetts, decarbonization of commercial and residential buildings will require an intervention in nearly every home and commercial structure.

The combustion of oil and natural gas for building heating is the largest end use contributor to emissions in these sectors. This is followed by the use of these fuels for hot water heating, cooking, and other processes, such as drying clothes. Given the cost and scarcity of low- or zero-carbon drop-in replacement fuels, coupled with the current and growing availability and applicability of heat pump technology – as well as induction cooking – and the practical necessity for residual 2050 emissions elsewhere in the economy, the building sector must approach near-zero emissions in the aggregate by 2050 in order for the Commonwealth to achieve net-zero statewide emissions in the same time frame. Although multiple technologies exist to decarbonize buildings, electrification of end uses, particularly through the use of highly efficient electric heat pumps and other building appliances, appear to be the dominant least-cost strategy (>90% residential heat pump or resistance; >95% electric water heating and cook top; >95% commercial heating, water, and cooking).

While technological solutions are currently available for the majority of building types, the regular turnover of heating equipment, appliances, and building envelope upgrades represent important practical limitations for how quickly this transformation can occur while ensuring that building occupancy remains cost-effective, comfortable, and healthy for businesses and families across the Commonwealth. Building heating equipment such as furnaces or boilers can have lifetimes as long as 30 years, while building envelopes are only retrofitted about once every 40 years at most. That means that buildings built today, or potentially heating equipment replaced today, could have similar energy use profiles out to 2050. The broad adoption of electric heating has important but manageable implications for the electric power system, further detailed in the *Energy Pathways Report*. Policy interventions are almost certainly needed in order to accelerate this "building plus grid" transition in order to meet interim and 2050 decarbonization targets, and to manage the transition so as to minimize disruption, unintended consequences, stranded investments, and potential related socioeconomic inequity.

Over the past decade in particular, during which the Commonwealth has created and maintained the nation's top energy efficiency programs, energy efficiency has been instrumental in halting the rise in emissions from residential and commercial buildings. As decarbonizing energy sources becomes the predominant strategy for reducing emissions, the role of efficiency will transition to be supportive of decarbonizing energy sources rather than a direct mitigation. First, efficiency decreases total demand for energy and lowers cost at the building level, including reducing the upfront cost of electrification by allowing a smaller HVAC system to be installed. Second, by lowering total energy demand, it also reduces the need for additional energy supply, reducing renewable energy system-wide build-out costs. Third, by lowering instantaneous peak demand, efficiency reduces the electrification-driven growth of load on the distribution system. As such, efficiency makes building decarbonization both feasible and cost-effective.

The high-level findings of this study are presented below. The analysis is focused on direct emissions from buildings and does not evaluate the emissions from electricity demanded by buildings, consistent with the approach used by the Department of Environmental Protection's Greenhouse Gas Emissions Inventory.

Building Decarbonization Strategies

- Electric technologies such as air source heat pumps are available now and ready to be scaled for a large portion of the Massachusetts building stock, especially single family and small multifamily homes and offices. More complex building types and end use needs may require more complex heat pump solutions or may not presently be cost-effective but will still need to be decarbonized by 2050 to meet the emissions reduction targets.
- New and existing buildings can be decarbonized using all-electric technologies, drop-in low- and zero-carbon fuels, or hydrogen as a fuel for space and domestic water heating.
- Low- and zero-carbon fuels could support building decarbonization, particularly in large commercial and institutional building types that are difficult or more expensive to electrify. Low- and zero-carbon fuels may not necessarily require new end-use equipment. These technologies have some constraints: they are not presently readily available and may likely take longer to scale; they are also expected to be more expensive to use relative to operating an electric heat pump , and may face fuel supply limitations due to scarce or expensive feedstocks.
- Given their niche applications, potentially lower level of adoption and longer time horizon to scale, the optimal application of hydrogen and decarbonized fuels for such harder-to-decarbonize building types is not evaluated here but is a potential area of future study.
- Reducing energy demand via efficiency and shifting loads supports the above decarbonization strategies, by lowering building-level energy costs; renewable energy (electricity and fuels) production and build-out costs; and the need for distribution system investment.

New Buildings

- New construction between 2020 and 2050 is projected to account for 19% of the building stock (by square footage) by 2050. Much of this growth (about 60%) is projected to occur over the next decade driven by demographic trends, primarily driven by small residential buildings.
- Annual emissions from new buildings are anticipated to grow to nearly 1.5 MMT CO_2 by 2050. This projection assumes a slow and steady advancement of the building code through 2050 without the initial implementation of a high-performance/zero on-site emissions policy. The adoption of a high-performance/zero on-site emissions new construction code in 2030 could reduce annual 2050 emissions from residential and commercial new construction by 0.8 MMT CO_2 (54% reduction) and by 1.30 MMT CO_2 (87% reduction) if implemented in 2023.

- Given the rapid pace of forecasted growth over the next decade, early action in enacting a net-zero on-site emissions code will help to achieve interim emission reduction targets and avoid the lock-in of combustion-based equipment and low-performance building envelopes that will be more expensive for homeowners in particular to run in, or retrofit in advance of, 2050 due to higher fuel costs or future cost-of-emission allowances. Early implementation of a code would save 22 $MMTCO_2e$ in cumulative emissions.

Existing Buildings

- 81% of the expected building stock in 2050 has already been built and placed into operation. This comprises 5.9 billion square feet across the Commonwealth with the following characteristics:
    - 74% of the current built square footage is composed of residential buildings;
    - 65% of the current built square footage (66% of residential buildings and 62% of commercial buildings) was built before 1980;
    - 81% of households and 88% of commercial floorspace uses natural gas, fuel oil, or propane onsite (with the remaining buildings predominantly using electric resistance technologies to provide heating and other thermal services).
- Due to current operational cost savings, buildings using fuel oil, propane, or electric resistance today are prime candidates for heat pump technologies. In the long run, the use of natural gas will become less cost competitive relative to electrification even without considering carbon cost.
- Electrification can be implemented with minimal additional interventions in most residential homes. Envelope interventions (added insulation, high-performance windows, extensive air-sealing/weatherization) can make electrification more cost-effective but may require the addition of ventilation to maintain or improve healthy indoor air quality.
- Larger buildings require and benefit from simultaneous system upgrades and improvements to ventilation to facilitate electrification.
- Deep envelope interventions and the use of highly efficient equipment typically require more upfront investment but are generally as cost-effective in terms of dollars spent as less invasive actions per unit of energy saved.
- The largest and most cost-effective decarbonization opportunity for the Commonwealth is its small residential buildings (<4 units) which are relatively easy to modify and comprise over 60% of statewide building emissions. This is particularly the case for residential buildings built before 1950 (32% of emissions while only 21% of floorspace) which have the most potential to lower occupant costs through energy efficiency upgrades.
- Buildings that have high ventilation loads, such as laboratories and hospitals, also exhibit a potential for relatively low-cost efficiency measures. However, these are of limited scale relative to the small buildings stock.

Sector Wide Considerations

- In order to achieve required emissions reductions in and before 2050 in the Buildings Sector, significant growth in the pace and scale of heating system retrofits is required. For the residential sector, that translates to an average of nearly 100,000 homes installing heat pumps or other renewable thermal systems each year for the next 25-30 years. The commercial sector requires a comparable level of effort. Given the related increasing demand on the electricity distribution system and declining demand on the gas distribution system, this transition will need to be actively managed to ensure safety, reliability, and cost-effectiveness.

- Achieving efficiency targets that help ensure reliability and cost-effectiveness will require significant growth in both number of buildings and depth of efficiency measures pursued, with nearly all homes needing some level of efficiency upgrade by 2050. This includes many, mostly older, homes receiving deep energy retrofits (e.g., more insulation, new windows) together with a new clean heating system.
- Decarbonization of more complex buildings will require more customizable solutions for both thermal decarbonization and efficiency. While many solutions exist today, there is an opportunity for future research and piloting to determine cost-effective decarbonization solutions for more complex buildings.

2 Introduction and Study Context

This technical report focuses on GHG emissions reductions in commercial and residential buildings, with the intention of providing insights into technological, market-based, and policy-driven opportunities and barriers for decarbonizing those sources. This analysis focused on residential and commercial buildings which make up the majority of emissions in the built environment (over 80%). Emissions from industrial buildings were analyzed at certain points, particularly with regards to decarbonization opportunities around space and water heating and energy efficiency; industrial non-energy emissions were explored in the *Non-Energy Sector Technical Report.* The Buildings Sector research team focused primarily on residential and commercial buildings. Direct GHG emissions from the Building Sector in Massachusetts includes fossil fuels burned on site – primarily for space heating (75%) and water heating (23%). Additionally, buildings consume electricity[1] to power ventilation, lighting, cooling, appliances, equipment, and other services. This report analyzed how to decarbonize the Buildings Sector by 2050.

2.1 Emissions Trends in Massachusetts' Building Stock

According to the 2017 Massachusetts Greenhouse Gas Inventory, on-site combustion of fossil fuels in the residential and commercial buildings subsectors was responsible for 27% of statewide GHG emissions in the Commonwealth. Emissions in these sectors have generally trended downward since 1990, going from a range of 23 to 25 $MMTCO_2e$ in the early 1990s to a range of 18 to 21 $MMTCO_2e$ in the past 5 years (Figure 1). During this time period, the Commonwealth was constructing new residential and commercial buildings; the total square footage of built space increased 16% since 1990. While annual emissions from the building sector can be variable based on weather fluctuations, the trend of emissions reduction with a growing square footage can generally be attributed to: growing stringency in new construction codes, existing building energy efficiency, and fuel switching—primarily from fuel oil to natural gas.

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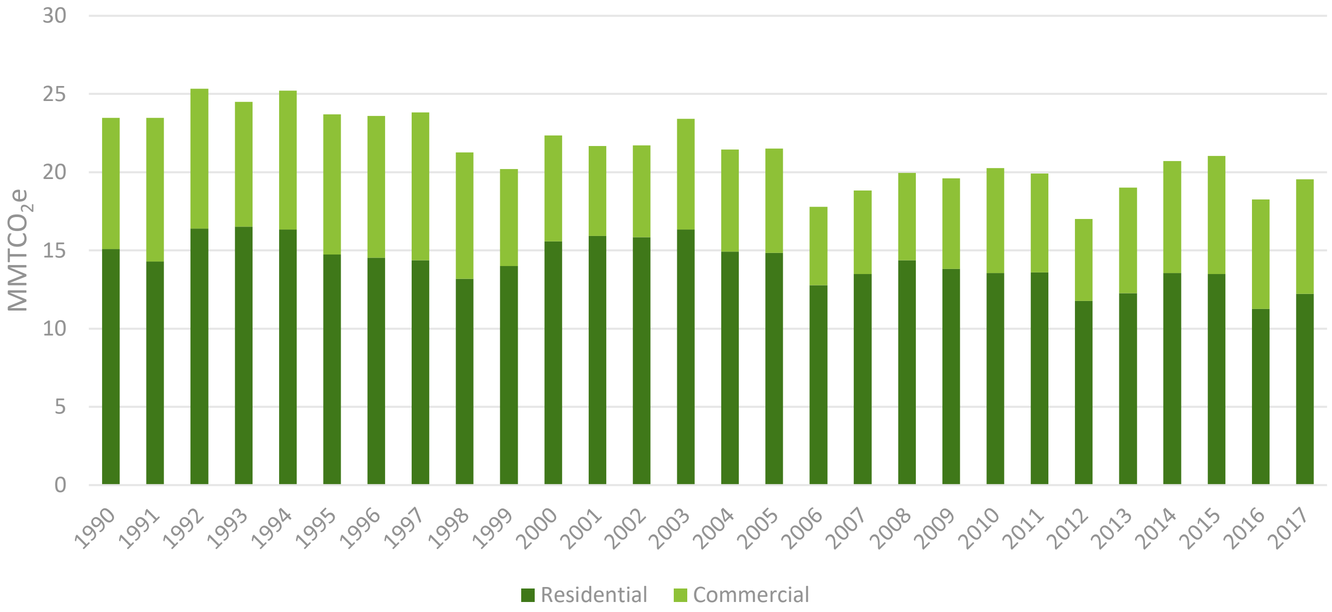
[1] Emissions for the Commonwealth's buildings sector are generally reported only as those associated with on-site fuel combustion. They are designated as "Scope 1" emissions in corporate accounting frameworks; that is, direct emissions from sources owned or operated by an entity. See, e.g., https://www.epa.gov/greeningepa/greenhouse-gases-epa with emissions associated with electricity consumption accounted for separately. The Commonwealth reports all emissions associated with the consumption of electricity in the Commonwealth, including for consumed electricity produced outside the Commonwealth, as "Electricity Sector" emissions.

Figure 1. Massachusetts GHG Emissions from the Buildings Sector, 1990-2017



From 2011-2019, Massachusetts was ranked #1 in the US for energy efficiency by the American Council for an Energy-Efficient Economy (ACEEE).[2] The Commonwealth has nation-leading energy codes and a stretch energy code which drives energy performance of new construction and renovation. Additionally, the robust energy efficiency program, Mass Save, provides efficiency for both end uses of energy (such as lightbulbs or HVAC equipment) and for building envelope improvements (such as insulation and air sealing), which reduce the thermal load needed to keep buildings comfortable.

Since 1990, the majority of fuel switching within a residential or commercial building has been from fuel oil and petroleum products to natural gas for heating, hot water and other thermal needs.[3] This switch has resulted in onsite GHG reductions, since fuel oil (74.0 kg per MMBTu) and other petroleum products emit more CO_2 than natural gas (52.9 kg per MMBTu). Additionally, increased utilization of condensing furnaces and boilers across fuel types have improved fuel conversion efficiency. Building electrification, specifically switching from natural gas to heat pump based electric heating systems, is happening at a small scale and has led modest to-date reductions in the Commonwealth's building sector GHG emissions.

2.2 Decarbonizing Buildings in the Context of the Broader Energy System

In order to understand how energy used in the building sector intersects with the larger energy system, the *Massachusetts Decarbonization Study* included an analysis of energy supply system decarbonization using several building demand side pathways and building-sector analyses. The findings of the energy supply system analysis are detailed in the companion *Energy Pathways Report* and summarized in the *Massachusetts*

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[2] Massachusetts Executive Office of Energy and Environmental Affairs. *Massachusetts Named Most Energy Efficient State in Nation*. 2019 https://www.mass.gov/news/massachusetts-named-most-energy-efficient-state-in-nation-0.
[3] Massachusetts Energy Policy Planning & Analysis Division. *How Massachusetts Households Heat Their Homes*. 2017. https://www.mass.gov/service-details/how-massachusetts-households-heat-their-homes

Decarbonization Roadmap to 2050, with buildings-relevant findings discussed below. The findings from the Energy Pathways analysis were used to parameterize the buildings sector-specific analysis detailed in this report.

The *Energy Pathways Report* studied eight decarbonization pathways to 90% emissions reduction economy-wide (compared to the 1990 baseline), four of which explored the building energy systems:

- *All Options:* A benchmark case optimizing for least cost approaches to decarbonization without specific constraints. This pathway resulted in a high degree of building efficiency and electrification.
- *Limited Efficiency*: This pathway constrained the amount of energy efficiency in residential and commercial buildings but had the same high degree of electrification as described in *All Options*. It resulted in 18% more electricity demand (18.7 TWh) and had significant cost and infrastructure implications compared to the *All Options* pathway.
- *Pipeline Gas:* This pathway matched the aggressive efficiency measures deployed in the *All Options* pathway but assumed that buildings were only partially electrified. Higher displacement of pipeline gas fossil fuels with biofuels was used to reach the emissions constraints.
- *DER Breakthrough:* This pathway explored cost reductions for distributed energy resources and resulted in high levels of rooftop solar (17 GW vs 7 GW from *All Options*), together with more behind the meter storage and flexible load, including vehicle-to-grid charging. Buildings in this pathway had the same high levels of efficiency, electrification, and demand side energy use as in *All Options*.

These pathways were implemented by adjusting the timing and level of adoption of energy efficiency and electrification. Figure 2 shows residential heating service demands and the energy sources meeting that demand. Figure 3 and Figure 4 respectively show the residential and commercial equipment sale shares, overall stock, and final energy consumption. Figure 5 shows the increased electricity demand associated with transportation and heating electrification. What is notable about these trends is the rapid pace and depth of action in order to transform the building stock to meet these targets of 90% emissions reduction. Figure 2, Figure 3, Figure 4, and Figure 5 represent technology transitions implemented on a natural replacement cycle, at the end of equipment depreciable life.

Figure 2. Massachusetts residential heating service demand. The allocation of service demand to a final energy type is shown by the stacked area. Trends in building shell and heating degree days (HDD) lead to modest reductions in the baseline space heating demand. Aggressive building shell measures in the All Options and Pipeline Gas pathways reduce space heating service demand to 70% of the baseline. High efficiency washing machines and dish washers result in a drop in demand for hot water.

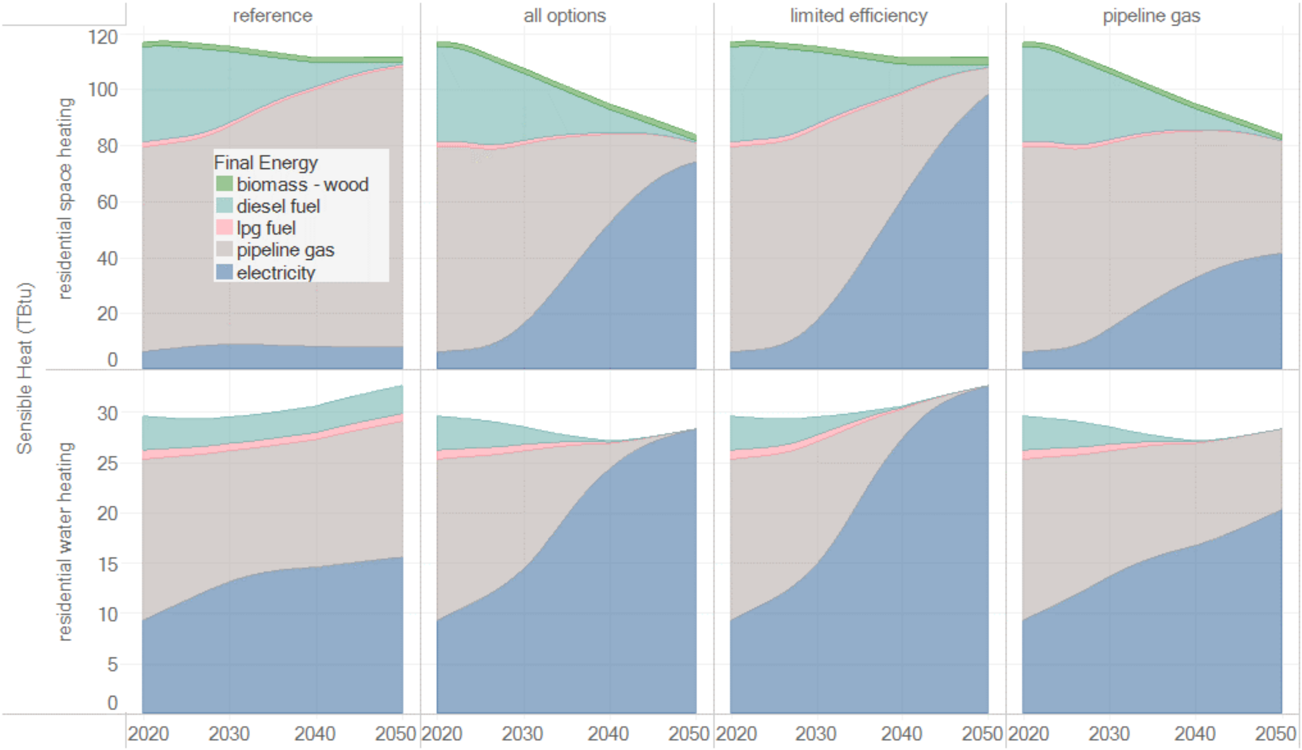


Figure 3. Massachusetts residential building electrification. Subsectors with high electrification potential—space heating, water heating, and cooking—are shown for the All Options and Pipeline Gas pathways. Annual sales shares (based on input assumptions) are shown in the left-hand figures, the resulting technology stocks in the middle figures, and final energy demand in the right-hand figures.

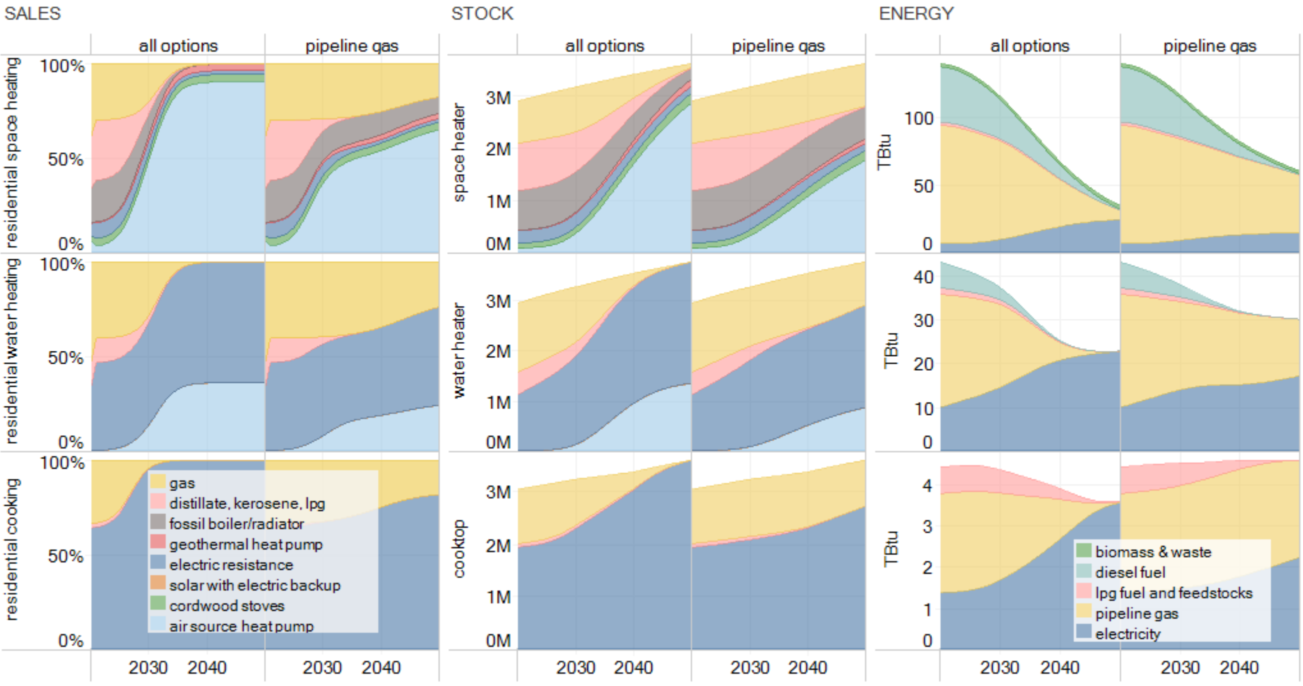


Figure 4. Massachusetts commercial building electrification. Subsectors with high electrification potential—space heating, water heating, and cooking—are shown for the All Options and Pipeline Gas pathways. Annual sales shares (based on input assumptions) are shown in the left-hand figures, the resulting technology stocks (by TBtu/year, not unit to account for variety of commercial applications) in the middle figures, and final energy demand in the right-hand figures.

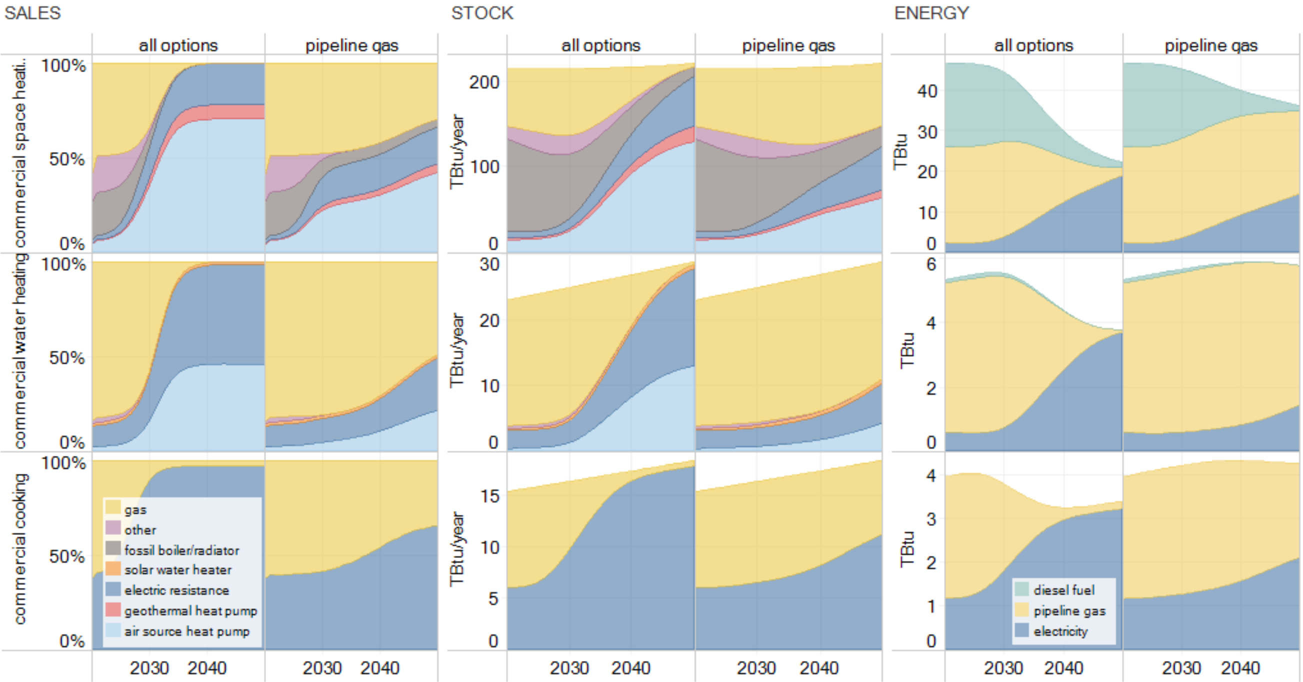
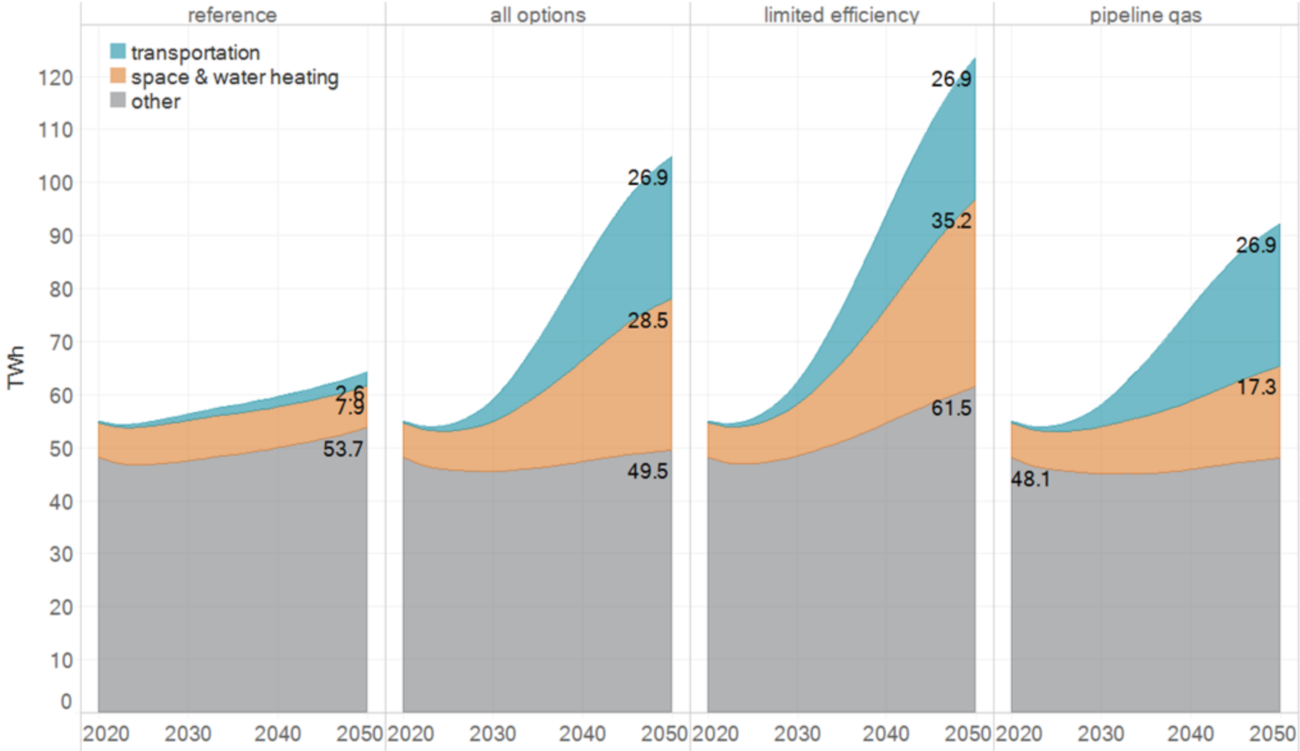


Figure 5. Annual electricity final demand in Massachusetts for transportation, heating, and other (all other loads). T&D losses are not included in final demand. The All Options and Pipeline Gas pathways have identical levels of final heating demand while the limited efficiency has a lower level of final service demand. For example, Limited Efficiency has a higher building heating demand due to poorer envelopes, while the other two pathways have identical, higher, levels of heating demand that are served by differing levels of gas and electric transformations.



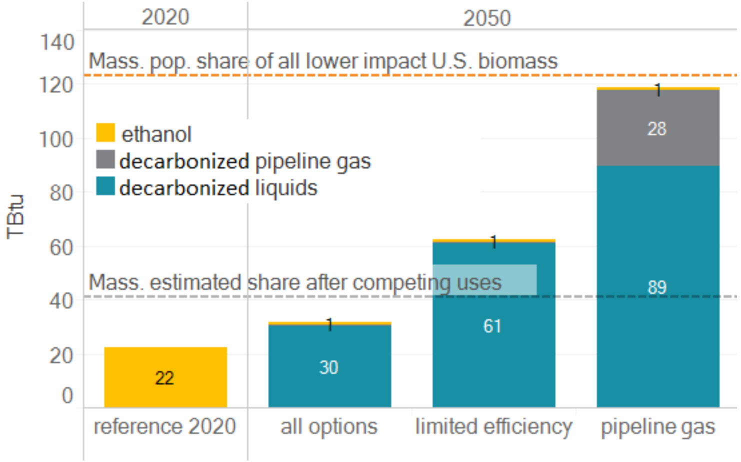
In all cases, electric heating, driven by heat pumps, became the largest share of HVAC sales by 2030. Additionally, building-level energy efficiency gains are assumed to decrease service demand by 30% from 2020 to 2050 in the All Options and Pipeline Gas pathways. The Limited Efficiency and Pipeline Gas cases assume a lower rate of technological penetration of efficiency and electrification respectively. Achieving the Commonwealth's decarbonization target is shown to be possible with each of the pathways; however, the Energy Systems analysis demonstrates that each has tradeoffs and uncertainties, including:

- Across all pathways analyzed, both transportation and buildings systems in Massachusetts shifted towards electricity. In order to decarbonize, all pathways required significant investment in electric distribution infrastructure and transformative growth of clean generation.
- Due to the significant growth in electrified heating, the electricity system is expected to shift from summer-peaking to winter-peaking over the next 30 years. During that same time horizon, the electricity generation mix will be transforming. The interaction between buildings and the grid, while they are both in the process of changing, will evolve in potentially uncertain ways. This includes potential disruption around strategies to managing system peak and changes in the goals for building characteristics as the needs of the grid shift.
- Because the electric vehicle charging assumed in the baseline already significantly increased distribution system peak loads, the incremental impact of building electrification was a relatively modest 30% increase. This incremental impact was greater when EV adoption was lower, or when vehicle charging flexibility was greater.
- Both the available volume and costs associated with decarbonized gas, required in low electrification pathways, are uncertain.
- In the pipeline gas pathway, average gas rates increased by 2-3 times due to a combination of biogas cost, lower gas pipeline throughput, and impacts of the marginal cost to abate carbon emissions elsewhere in the economy required to allow the continued combustion of natural gas in buildings.
- The Limited Efficiency pathway resulted in significantly higher investment in electric generation, transmission and distribution systems, including a 50% higher offshore wind build from 2030 to 2045 compared to All Options.
- Efficiency measures in buildings and industry have historically been cost-effective and are expected to remain cost-effective as carbon emissions limits tighten over time. By 2050, every $1 invested in efficiency returned $1.50 in modelled avoided energy costs.
- Load flexibility in buildings, particularly for water heating but also for electrified HVAC, was found to be a least-cost way to help manage the grid for high rates of electrification.
- The DER Breakthrough pathway included significant deployment of flexible load— such as vehicle-to-grid and flexible HVAC and water heating—across buildings, which helped to reduce system transmission and distribution costs. These flexible loads served both their primary purpose as well as acting as storage, especially in the case of EV batteries. Even with the higher demand-side costs for flexible equipment, the DER Breakthrough pathway was found to be marginally lower cost in 2050 than the All Options scenario. Due to the combined effects of the timing of renewable generation and a wind-heavy system, distributed battery storage played only a small role in balancing the bulk power system.

A fifth energy pathway which constrained offshore wind deployment found that less wind generation resulted in significantly higher electricity generation costs in the winter. This pathway demonstrated the favorable seasonal alignment of offshore wind electricity generation and electric demands from thermal electrification.

The viability of a reduced-carbon pipeline gas supply was explored thoroughly in the *Energy Pathways Report*. Detailed further in that report, limitations were identified around the supply of viable bioenergy feedstocks and the costs of synthetic gas fuels. The Princeton Net-Zero America Project identifies a national limit (12 quads per year) of bioenergy production based on available organic waste feedstocks and the repurposed of land for corn-ethanol (but no new land for purpose grown energy crops). After expected population growth and competing uses of these resources (chemicals and bioplastics) are accounted for, Massachusetts' population-weighted future share of national bioenergy supply is approximately 41 TBtus per year. The practical implications of this are shown in Figure 6.

Figure 6. Massachusetts imports of decarbonized liquid hydrocarbons. These fuels are made in the rest of the U.S. (or internationally) for export to Massachusetts and the rest of the Northeast using technologies that imply carbon neutrality. The orange dashed line represents Massachusetts's population share of U.S. biomass production that limits purpose-grown feedstocks to the same land footprint currently used for ethanol production, plus all available crop wastes and residues. The grey dashed line is the share after taking into account competing uses such a chemical feedstock. Consumption of ethanol declines as vehicles electrify.



Currently, Massachusetts imports approximately 22 TBtus of ethanol as a gasoline additive. With vehicle electrification, the demand for this ethanol additive shrinks to 1 TBtu in 2050. This current biofuel usage is replaced by a demand for decarbonized roadway fuels (mostly diesel) and aviation jet fuel that is met by approximately 30 TBtus of bioenergy in the All Options pathway. While this replaces and exceeds the current ethanol demand, it is still below Massachusetts's population-weighted share of biomass. By contrast, both the Limited Efficiency and the Pipeline Gas pathways would be expected to exceed Massachusetts's future share of national bioenergy supply. The Limited Efficiency pathway has a high decarbonized liquid demand due to limited improvements in aviation efficiency leading to increased demand there for decarbonized liquid fuels. In the Pipeline Gas pathway, lower building electrification leads to continued demand for methane in buildings (164 Tbtu) relative to the high electrification All Options pathway. Because it is more cost effective to replace liquid fuels, only 28 TBtu of this gas demand – or 17% – is met by decarbonized gas. Additional bio-based decarbonized liquid fuels (89 Tbtu) were imported to further displace fossil fuels in the transportation sector. A low-electrification pathway results in a relatively higher reliance on fossil natural gas, and a need to decarbonize deeper in other sectors to reach Massachusetts' GHG reduction targets. This increases pathway costs overall and greatly exceeds Massachusetts' population share of bioenergy resources. Further, it places more reliance on technologies that have yet to be demonstrated to cost-effectively scale: both decarbonized gas and decarbonized liquid fuels.

In summary, the findings of the *Energy Pathways Report* indicate that that widespread adoption of electrification and increased efficiency measures together is likely to be a lower cost decarbonization strategy than an approach that continues to rely on pipeline gas or one that defers or fails to deploy additional energy efficiency.

The *Energy Pathways Report* analysis utilized high-level representations of the residential, commercial, and industrial sector to evaluate integrated, system-wide transformations. This report adds additional analysis that explores the implications of such decarbonization for Massachusetts' diverse building stock. This analysis further examines differences in building types by building age and use to answer two sets of research questions focusing on electrification and efficiency:

- **Electrification**: The integrated analysis assumed that between 64% (Pipeline Gas) and 86% (All Options) of heating would rely on some electric technology by 2050. Similar ranges were assumed in the commercial sector.
    - *What buildings types can be feasibly or cost-effectively electrified today? Are some more cost-effective to electrify than others? If so, which ones?*
- **Efficiency**: The integrated analysis examined two levels of efficiency-driven reduction in residential service energy demand for home heating between now and 2050: a 7.5% (Limited Efficiency) and 30% (All Options) reduction. Similar levels of reduction were also represented for domestic hot water (DHW) and in the commercial and industrial sectors. Efficiency and reductions in service demand have benefits at both the buildings and supply system levels. In certain instances, but rarely for residential housing, the cost of building level interventions may exceed the building level savings while still delivering net savings at the system level.
    - *What type and levels of efficiency are most cost-effective for which building types to achieve the efficiency targets described above? Is a "one-size-fits-all" approach to efficiency more effective, or are there potential cost savings from a more tailored approach based on building characteristics?*

This report examines these questions with detailed modeling of building energy consumption for the most common building types and vintages in Massachusetts. The analysis focuses on how different levels of efficiency actions can support electrification at the building level for both new and existing buildings. The report then explores the sector-wide scaling of different efficiency strategies.

2.3 Solutions Outlooks

This section provides background and context around the Building Sector decarbonization strategies and technologies which are discussed and included in the analysis in Chapters 3-6. Further detail on technologies can be found in Appendix C: Technology Profiles.

2.3.1 Electrification

To maximize opportunities for emissions reductions, electric technologies are most cost-effective and easiest to install at either the time of building construction or renovation, or to replace existing equipment that has reached its natural end-of-life. Given that most technologies for heating, hot water, and cooking have a lifespan ranging from 8 to 30 years, replacing fossil fuel-dependent technologies need to begin immediately to avoid lock-in or premature retirement. Heat pump technologies that use electricity to provide space heating are a major component of building decarbonization strategies.[4] **Air-Source Heat Pumps (ASHP)**, while very common across the globe for both space heating and cooling,[5] are currently only used by 11% of homes in the US for their primary heating needs, and 90% of these homes are in warm climates with limited heating needs.[6] Highly efficient "cold climate" ASHPs have gained a foothold through the Northeast over the past decade. These widely available systems are rated to maintain high levels of efficiency and heating capacity even in sub-zero temperatures. ASHPs are highly efficient technologies that are projected to improve in the coming decades;[4] currently ASHP effective efficiencies range from 220-350%, compared to fossil fuel furnace and boiler efficiencies which typically range from 65-99%.

Today, ASHPs in an air-to-air configuration can both heat and cool air (for space conditioning), or heat water in an air-to-water configuration (most commonly for domestic water heating but could also heat water for radiant space heating water). **Variable refrigerant flow (VRF)** systems, particularly those with zone-to-zone heat recovery, have been gaining popularity in commercial applications, growing at a compounded annual growth rate of 11% since 2015.[7]

Air-Source Heat Pumps come in several variations, but all condition air through a heat exchanger that transfers heat between outside air and the refrigerant in the heat pump. Another technology in the heat pump family is **Ground-Source Heat Pumps** (GSHPs), which have a similar mechanism, but the heat exchanger transfers heat between the refrigerant in the heat pump and a buried loop, which is typically either in the ground or submerged in water.[8] GSHPs account for about 10% of nationwide heat pump installations.[6] While GSHPs are more efficient[9] and last longer than ASHPs, their installation is more complex and their initial capital cost is higher. Over the past 15 years, GSHP systems have predominantly transitioned away from open loop systems that that circulate ground water to the heat pump to transfer heat, towards closed loop systems which typically circulate a water/antifreeze mixture through plastic tubing that is buried in the ground or submerged

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[4] While heat pumps are highly efficient and electric, they do rely on the use of refrigerants. The companion *Non-Energy Sector Technical Report* assesses the potential greenhouse gas impact from the increased use of high global warming potential (GWP) refrigerants associated with heat pump technologies, as well as potential mitigation strategies from the use of alternative low GWP refrigerant. Strategies to deploy heat pumps should thus: (1) be supported by adequate regulation of refrigerants, and (2) ensure that there is sufficient workforce training and resources for recovery of refrigerants from existing systems as well as the appropriate installation of new systems to minimize leakage.

[5] Columbia University SIPA – Center on Global Energy Policy. *Decarbonizing Space Heating with Air Source Heat Pumps*. 2019. https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps

[6] NREL Electrification Futures Study (December 2017): https://www.nrel.gov/docs/fy18osti/70485.pdf, December 2017

[7] ACHR News. *VRF Market Expected to Hit $24B by 2022*. 2017.https://www.achrnews.com/articles/134465-vrf-market-expected-to-hit-24b-by-2022

[8] Department of Energy. *Geothermal Heat Pumps*. https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems/geothermal-heat-pumps

[9] For cold climates, GSHPs outperform ASHPs by about 45% in heating, and 30% in cooling when accounting for seasonal effects. https://www.phius.org/NAPHC2016/Jacobson GSHP ASHP.pdf

in water. With the advent of closed loop systems, the number of applications for which GSHPs are feasible has increased and the Commonwealth has seen an increase in these systems in the past decade. Even so, unlike ASHP that only need access to outdoor air, because of configuration requirements necessitating access to underground, GSHPs are expected to be technologically feasible in 76% of buildings in the Commonwealth.[10]

In addition to residential installations of GSHPs, such as the approximately 600 installed through the Massachusetts Clean Energy Center (MassCEC),[11] there have been several K-12 Schools that are implementing GSHP systems, such as the King Open School in Cambridge, Belmont Middle and High School (under construction), and the Maria Hastings Elementary School in Lexington. Boston University is also constructing a 17-story, 345,000 square foot office and classroom building that will be thermally supported by thirty-one 1,500-foot-deep wells to the east of Kenmore Square. These examples of early adopters demonstrate potential for wider GSHP deployment. Various firms are innovating with methods to drive down the costs through virtual site assessments and screening, district applications, improved drilling technology, and workforce development. Facilitating such activity with early industry support would lead to larger and more rapid deployment of this technology.

While the market for heat pumps, both ASHP and GSHP, in Massachusetts has grown, it has not yet achieved the market share and scale of growth necessary to reach the penetration described in any of the pathways in the *Energy Pathways Report*. Several regional market assessment studies[12] have been conducted to understand the heat pump market in the Northeast and have identified several potential challenges to widespread adoption. Some of the challenges include: generally low awareness of heat pump technology amongst both consumers and HVAC contractors; low cost of natural gas; potential need for electrical upgrades to support the installation of a heat pump; limited installation best practices for whole-home heating; insufficient workforce at the projected scale; and higher upfront cost of heat pump system compared to a furnace or boiler.[13] As heating equipment is often replaced at the end of system life or failure, it may be

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[10] This report analyzed the Massachusetts Land Parcel Database filtered by plots with building area https://datacommon.mapc.org/browser/Land%20Use. Plot heat rejection tonnage was estimated using 250 sf/ton benchmark, and 400 sf required land area per ton. This area was compared against the non-building land area to assess whether plots are compatible. The results were that 70% of Boston Metro was compatible, 86% of the Southeast MA was compatible, and the rest of state was 84% compatible. This calculated to a statewide average of 76% of buildings being compatible with special requirements necessary for installation of a GSHP.

[11] Massachusetts Clean Energy Center. *Incentives for Ground Source Heat Pumps.* https://www.masscec.com/incentives-ground-source-heat-pumps and internal presentation.

[12] A Better City (ABC). *Thermal Electrification of Large Buildings in the Commonwealth* https://www.abettercity.org/assets/images/Buildings%20Electrification%20Report%20Reduced.pdf; Northeast Energy Efficiency Partnerships (NEEP). *Air-Source Heat Pump Market Strategy Report* (2017) https://neep.org/sites/default/files/NEEP_ASHP_2016MTStrategy_Report_FINAL.pdf; Northeast Energy Efficiency Partnerships (NEEP). *Variable Refrigerant Flow (VRF) Market Strategies Report* (2019) https://neep.org/sites/default/files/resources/NEEP_VRF%20Market%20Strategies%20Report_final5.pdf; Harvard University Institute of Politics. *Accelerating Building Electrification in New England* (2020). https://iop.harvard.edu/sites/default/files/sources/program/IOP_Policy_Program_2020_Accelerating_Building_Electrification_in_New_England.pdf

[13] Cost can present additional challenges for heat pump adoption in multifamily homes, for rental units (due to a split in incentives between the building owner and their tenant), and for low- and moderate-income communities with a high sensitivity to energy prices.

challenging for a building owner to successfully transition from a fossil fuel system to a heat pump without advanced planning.

Despite these challenges, there are several potential tailwinds that can help accelerate the transition to heat pumps. Homeowner demand for cooling is increasing, driven by consumer preferences and warmer summers. Heat pumps can provide cooling to meet this demand in homes that do not have central air and may otherwise rely on less efficient window or portable AC units. Additionally, the total cost of ownership accounting for upfront installation, energy costs, and maintenance can be competitive with legacy system, especially fuel oil heating. Heat pumps have also reached a point where they are proven to work as a building's only heating source.

The Mass Clean Energy Center's (MassCEC) Whole Home Heat Pump Pilot[14] has installed nearly 100 residential heat pumps as the exclusive heating source or "Whole Home." The Pilot includes both new and existing small multi-family homes, with most of the existing homes built before the 1940's. The year-long program is still collecting results. MassCEC and DOER have also supported community driven HeatSmart campaigns that aim to develop local consumer learning though grassroot campaigns and increase contractor experience. The program operated in 15 communities and provided funding for over 450 installation contracts. On the commercial side, MassCEC supported over 100 large VRF projects from 2016-2019.[15]

HEAT PUMP SUCCESS IN MAINE:

Maine has recently set goals to aggressively pursue the installation and use of heat pumps. Between 2013 and 2019, the Efficiency Maine Trust incentivized over 46,000 installations, putting a heat pump in almost 10% of Maine homes. In 2019, the Maine Legislature established the goal to install 100,000 new high-performance heat pumps over five years in Maine through the Legislatively enacted LD 1766: An Act to Transform Maine's Heat Pump Market to Advance Economic Security and Climate Objectives. This legislation provides supplementary funding for the Efficiency Maine Trust's incentive programs.

[a] The Efficiency Maine Trust (2019). Beneficial Electrification: Barriers and Opportunities in Maine. https://www.efficiencymaine.com/docs/EMT_Beneficial-Electrification-Study_2020_1_31.pdf

While the number of heat pumps installed through demonstration projects and pilots are relatively small compared to the need to electrify heating in an average of 100,000 homes per year over the next 30 years (average pace in All Options pathway), they demonstrate the technical feasibility of heat pumps across configurations and applications, and provide an important foundation for the scaling of this industry. The pace of early growth can have significant consequences for when new technology adoption scales to a point to displace incumbent technologies such as natural gas or oil-based heating. By promoting learning, these programs can mitigate risks associated with technology switching; increase awareness and familiarly; and reduce costs by developing efficient supply chains and workforces

In addition to the electrification opportunities for building heating, electrification of domestic hot water systems through either an electric resistance or a heat pump water heater (HPWH) is also a decarbonization

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[14] MassCEC. *Whole Home Heat Pump Pilot* (2019). https://www.masscec.com/air-source-heat-pumps-1

[15] Massachusetts Clean Energy Center. *MassCEC VRF Program: Lessons Learned from 2 Years in the Field.* 2019. https://neep.org/sites/default/files/Peter%20McPhee%2C%20MassCEC.pdf

technology. In Massachusetts, only 20% of households have electric resistance water heaters, compared to an average of 45% nationally.[16] Though they have effective efficiencies of 3.0-3.5[6] times greater than electric resistance-based water heaters, HPWHs represented only 1% of the market. HPWHs are currently eligible for incentives under Mass Save when replacing an electric resistance water heater, but not when replacing a gas water heater. Decarbonization of water heating is possible through both electrification and switching to HPWHs which have significant efficiency improvements over electric resistance. NREL's Electrification Futures Study projects that costs for HPWH are expected to drop by 50% and seasonal efficiency is expected to improve by as much as 60%. In the commercial sector, HPWHs are relatively high cost compared to gas or electric resistance alternatives but may be advantageous in buildings with simultaneous heating and cooling demands such as commercial laundries, hotels, and restaurants.

2.3.2 **Energy Efficiency**

While the Commonwealth has a strong foothold in energy efficiency, the analysis in the *Energy Pathways Report* found that energy efficiency, alongside electrification, lowers the system-wide cost of decarbonizing the Commonwealth's existing building stock. A more detailed analysis of the cost effectiveness of energy efficiency by building type and vintage is discussed in Chapter 5 of this report. The residential energy efficiency treatments explored in this analysis include air sealing, improved insulation, efficient lighting and appliances, and smart thermostats, most of which are covered in some level by existing Mass Save incentives. Envelope improvement measures are expected to need significant growth, beyond what is currently offered and achieved through Mass Save, to both stay on target with the efficiency reductions from the *Energy Pathways Report* analysis as well as to improve cost-effectiveness of electrified heating at the building level. In commercial buildings, energy efficiency strategies typically include lighting, installing variable frequency or speed drives on fans and pumps, energy recovery, replacement of heating, cooling, and air handling equipment, and addition or commissioning of automated controls. As explored in Chapter 5, across residential and commercial buildings, there are efficiency opportunities in virtually all existing buildings, but older buildings and those that have not implemented energy efficiency measures in the past 10-15 years are likely to have a wider range of savings opportunities.

In addition to direct energy efficiency measures, there are numerous demand management and demand response programs currently available in Massachusetts and ISO-NE that may be expected to grow as the grid decarbonizes. Demand response systems react to signals provided by ISO-NE to reduce load during times of various supply side constraints such as periods of congestion or resource limitation. Demand management systems operate to limit demand charges for a specific site. Demand response and demand management systems are generally operated by demand response program aggregators and are typically not accessible to small or medium scale consumers. Future developments, such as new dynamic pricing signals, advanced metering infrastructure (AMI)[17], proliferation of distributed generation, energy storage and electric vehicles,

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[16] RECS 2009, referenced in NEEP 2012 Heat Pump Water Heater Market Assessment, https://neep.org/sites/default/files/resources/2012%20HPWH%20Report_FINAL_1.pdf

[17] Widespread rollout of AMI will enable the adoption of new pricing signals. For example, electricity rates could vary based on the carbon content of the grid (marginal pricing), when dirtier generation sources are brought online, electricity prices could increase to drive a change in user behavior. Through the integration of AMI, flexible loads on-site within a building could adjust to the increased price and ramp-down or shut-off entirely. Similarly, a signal could be broadcast during periods of peak load, which is current operation of demand management, or at times of low-renewable electricity generation to reduce load, and local energy systems could react accordingly.

and new end-user technologies could provide opportunities for wider consumer adoption and a smarter grid for increased demand management.

As the characteristics of electricity supply and demand continue to transform and decarbonize, load flexibility becomes increasingly important. Systems such as energy storage, HVAC or HVAC controls, water heating, and particularly EV charging[18] are examples of existing technologies which are already able to interface with demand management systems. Smart devices and systems are currently being installed for a range of customer benefits but have the potential to provide grid benefits as well. While flexible loads were not modeled explicitly in this report, the *Energy Pathways Report* analysis demonstrated that flexible loads can reduce costs and generation resource needs. While flexible EV charging is the largest resource of this type, some flexible building loads such as heating, cooling, and water heating provide grid and cost benefits. While electrification and energy efficiency are the primary strategies for decarbonization, where possible to incorporate load flexibility within buildings, there are system benefits over the next 30 years.

2.3.3 Additional Decarbonization Considerations

Alternatives to electrification, especially low-carbon fuels for space and water heating, were also considered. Decarbonized fuels (methane and oil) – generated by biological, thermochemical, or electrochemical processes – could be processed to a grade that is compatible with existing equipment. Biodiesel may be currently be blended up to 20% in home heating fuels.[19] Supplies of these fuels are considered limited and costly as discussed in detail above and in the *Energy Pathways Report*, but there may be a role to leverage such resources in some hard-to-electrify buildings or district systems. Woody biomass may also have some limited applications for space heating, especially when using waste wood or trimmings.

Hydrogen has the potential to be used as alternative to natural gas or fuel oil to generate energy from combustion in both new and existing buildings. Detailed further in Appendix C, hydrogen has limited applicability in the near term due to low availability of hydrogen-compatible appliances and equipment. Hydrogen blending into the natural gas system could potentially be used to partially decarbonize the natural gas system. The *Energy Pathways Report* found that electrolysis for use in hydrogen production in the Northeast may not scale until the 2040s when renewables have been built and pressure to further reduce emissions in combustion applications create markets for green hydrogen.

District energy systems, discussed further in Appendix C, present unique opportunities for decarbonization, as they vary greatly in terms of design, scale, and age in Massachusetts. Decarbonization of existing systems could be achieved through combustion of a drop-in bio- or renewable fuel, or by using an electric boiler. New district systems would need to utilize a zero or very low emissions intensity heat source. A recent study by the Home Energy Efficiency Team (HEET) proposes using a GeoMicroDistrict approach for neighborhood heating needs.[20] This approach would involve the deployment of a number of wells in a utility right-of-way to support

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[18] Eversource. *EV Home Charger Demand Response.* https://www.eversource.com/content/ema-c/residential/save-money-energy/explore-alternatives/electric-vehicles/ev-charger-demand-response

[19] NREL. Biodiesel Handling and Use Guidelines. https://www.nrel.gov/docs/fy06osti/40555.pdf

[20] GeoMicroDistrict Feasibility Study. HEET MA (2019). https://heetma.org/wp-content/uploads/2019/10/HEET-BH-GeoMicroDistrict-Final-Report.pdf

ground-source heating and cooling for a neighborhood. This study helped to inform a proposal by Eversource to conduct a demonstration project within Massachusetts to assess the viability of such a model.[21]

In the *Energy Pathways Report*, steam production in MA for district and industrial uses grew from 14 to 17 TBtu per year by 2050. This assumed that maintaining steam production was less expensive than changing equipment on the demand side. These systems installed a dual fuel boiler at their central plant that can use electricity or pipeline gas to make steam. Adding electric resistance to existing boilers is a relatively inexpensive step and that enhances system flexibly. This allows the steam generator or the district to take advantage of surplus low-cost and low-carbon electricity, which offsets the operating cost of increasingly expensive pipeline gas and keeps marginal curtailment low. Given the locational context and potential diverse implementation of district energy systems, this study does not make any future assumptions about their potential design or use of energy. Still, depending on the context, strategies to decarbonize new and existing district energy systems can provide some cost-effective and feasible mechanisms to reduce fossil fuel use and pursue efficiency and flexibility.

The analysis herein focuses on evaluating building-level strategies to identify the effectiveness and implications of electrification and varying levels of efficiency.

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[21] DPU Filing 19-120. https://d279m997dpfwgl.cloudfront.net/wp/2020/01/Initial_Filing_Volume_2_11-8-19.pdf

3 Approach

This report evaluates approaches to building decarbonization in Massachusetts using 4 distinct steps:

1. Segmenting the current buildings stock to determine major building typologies and vintages in the Commonwealth and determining their aggregate area.
2. Projecting the growth of the building stock across the major typologies out to 2050.
3. Conducting building energy modeling for identified building classes and evaluating the impact of electrification and efficiency retrofit packages.
4. Evaluating sector-wide trends in emissions and energy from the adoption of such packages.

The methodology for each of these steps is described in this section. This approach is then used to assess the timing of new building codes in Section 4; evaluate building-level retrofit strategies in Section 5; and quantify the impacts of contrasting sector wide decarbonization strategies in Section 6.

3.1 Segmenting Massachusetts Building Stock

A set of 18 building-use typologies, across 9 generalized categories, is used here to represent the major building classes of Massachusetts' buildings stock. The generalized categories were used to define building electrification and efficiency packages specific to each category. The more detailed use-type classification aims to represent the physical design (size, systems, structure) and use (e.g., office space, residential). To capture relevant changes in building envelope and systems due to the implementation and evolution of the building code, the project team further segmented the stock into several vintages based upon the use class.

The Massachusetts Level 3 Parcel Database22 was used to inventory the typologies by vintage. Parcels were sorted into the typologies by Metropolitan Area Planning Council (MAPC) land use code as described in Appendix A: Land Use Codes used in Typology Mapping (Table 24).23 The typologies are defined in Table 2. Within each of these typologies, 3 to 5 vintages have been defined, yielding a total of 73 classifications to represent the Commonwealth. The vintages align with past energy code development.

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[22] Massachusetts GIS. *MassGIS Data: Standardized Assessors' Parcels*. 2020. https://docs.digital.mass.gov/dataset/massgis-data-standardized-assessors-parcels

[23] Massachusetts Division of Local Services. *Property Type Classification Codes Non-Arm's Length Codes and Sales Report Specifications.* 2016. https://www.mass.gov/files/documents/2016/08/wr/classificationcodebook.pdf

Table 1. Building Types evaluated in this study

Category	Building Typology	Vintages				
Small Residential	Single Family Residential	Pre-1950	1950-1979	1980-2000	Post-2000	New Construction
	Small Multifamily Residential (2-4 family)	Pre-1950	1950-1979	1980-2000	Post-2000	New Construction
Large Residential	Large Multifamily Residential (5-19 family)	Pre-1950	1950-1979	1980-2000	Post-2000	New Construction
	Large Multifamily Residential (20+ family, wood construction)	Pre-1950	1950-1979	1980-2000	Post-2000	New Construction
	Large Multifamily Residential (20+ family, steel construction)	Existing				New Construction
Small & Simple	Small Office (< 5,000 sf)	Pre-1980		1980-2000	Post-2000	New Construction
	Medium Office (5,000 to < 50,000 sf)	Pre-1980		1980-2000	Post-2000	New Construction
	Retail	Pre-1980		1980-2000	Post-2000	New Construction
	Supermarket	Pre-1980		1980-2000	Post-2000	New Construction
Large and Complex	Large Office (> 50,000 sf)	Pre-1980		1980-2000	Post-2000	New Construction
	Convention/Assembly	Pre-1980		1980-2000	Post-2000	New Construction
School	K-12 School	Pre-1980		1980-2000	Post-2000	New Construction
Warehouse	Warehouse	Existing				New Construction
Ventilation Driven	Laboratory	Pre-1980		1980-2000	Post-2000	New Construction
	Hospital	Pre-1980		1980-2000	Post-2000	New Construction
DHW Driven	Hotel	Pre-1980		1980-2000	Post-2000	New Construction
	Restaurant	Pre-1980		1980-2000	Post-2000	New Construction
Industrial	Industrial Processes	Process focused: low, medium, or high-grade heat				

Table 2. Building typology definitions.

Use Class	Description
Single Family Residential	Buildings that have one living unit per building footprint. Living area has been used for area calculations.
Small Multifamily	2 to 4-family residences, intended to represent the "triple decker" style that is prominent in denser cities in the Commonwealth. Living area has been used for area calculations.
Large Multifamily (5-19 Stories)	Defined as 5 to 19-family residences. Gross area has been used for area calculations.
Large Multifamily (Wood Construction) (20+ Stories)	Defined as 20+ family residences, with constructions consistent with wood structures. Gross area has been used for area calculations.
Large Multifamily (Steel Construction) (20+ Stories)	Defined as 20+ family residences, with constructions consistent with steel structures and a floor air ratio (FAR) indicative of buildings taller than eight stories. Gross area has been used for area calculations.
Office (Small)	Largely composed of buildings on tax parcels classified as multiple story offices, but also consists of administrative buildings linked to public owners. Includes unclassified building types and serves as a catch-all for buildings not mapped to more distinctive typologies. Buildings under 5,000 ft^2 were considered "small".
Office (Medium)	Same as Office (Small), but covers buildings between 5,000 ft^2 and 50,000 ft^2 were considered "medium".
Office (Large)	Same as Office (Small), but covers, buildings over 50,000 ft^2 were considered "large".
Retail	Standalone retail, laundromats, stores in malls, and even property types such as health clubs, marinas, and gas stations
Supermarket	Standalone Supermarkets
Convention / Assembly	Arenas, auditoriums, large restaurants, movie theaters, libraries, and some college or university buildings. Convention/assembly is similar to office in that it's not as specifically defined as other commercial typologies so specific property keys without a clear mapping were mapped to it based on their lack of fit with specific typologies.
School (K-12)	Public and Private K-12 schools only. (Higher education buildings have been segmented per their predominant use type, not as a singular campus.)
Hospital	Buildings for providing medical and surgical treatment, including outpatient facilities.
Laboratory	A building equipped for scientific experiments, research, or teaching, or for the manufacture of drugs or chemicals.
Hotel	Inns, motels, and hotels
Restaurant	This typology is defined as standalone restaurants only.
Warehouse	Storage facilities including cold and industrial storage
Industrial	Factories and other premises used for manufacturing, altering, repairing, cleaning, washing, breaking-up, adapting, or processing any article.

As of 2016, there were over 5.9 billion square feet of residential and commercial buildings in the Commonwealth broken down by segment and vintage in Figure 7 and Figure 8. Residential buildings dominate the building stock, representing 74% or 4.3 billion square feet. Single family residences alone represent 49% of the Commonwealth's building stock, or 2.8 billion square feet. Combined with Small Multifamily residential buildings, these two building types represent 62% of the Commonwealth's building stock, or 3.6 billion square feet. Commercial buildings represent 23% of the buildings stock, or 1.3 billion square feet, and industrial buildings 3%, or 196 million square feet. Sixty-five percent of the Commonwealth's buildings, or 3.8 billion square feet, were originally built prior to 1980. This proportion is consistent across residential, commercial, and industrial buildings. A breakdown of the buildings stock in the residential and commercial subsectors follows.

Figure 7. Percentage of Massachusetts built square footage by typology and vintage for residential.

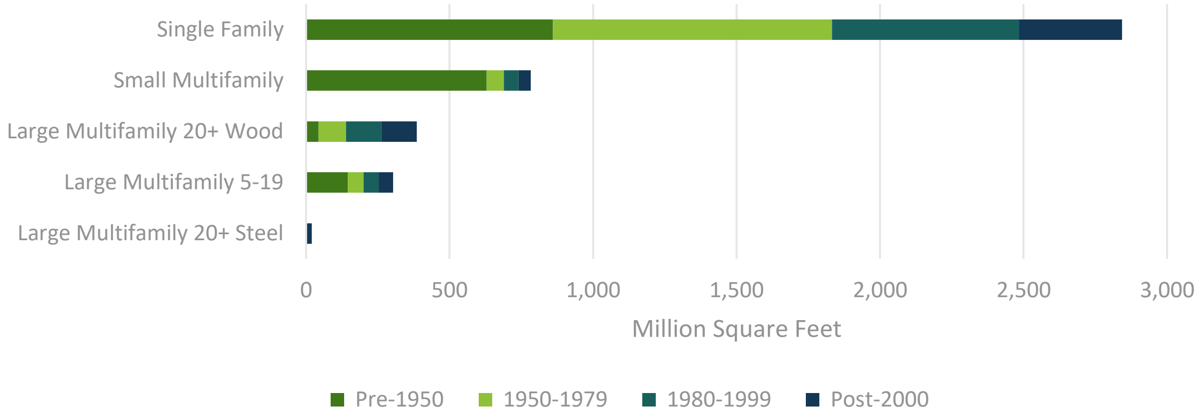
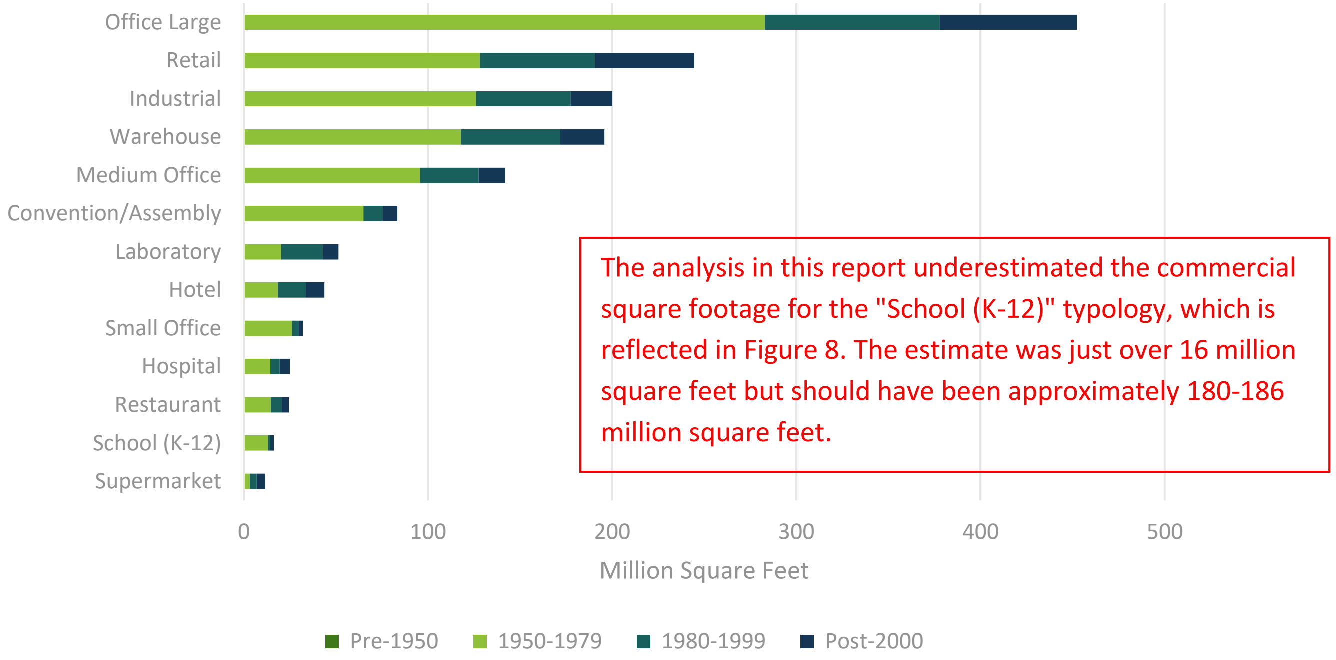


Figure 8. Percentage of Massachusetts built square footage by typology and vintage for commercial buildings. Note differing scale from Residential.



The analysis in this report underestimated the commercial square footage for the "School (K-12)" typology, which is reflected in Figure 8. The estimate was just over 16 million square feet but should have been approximately 180-186 million square feet.

Residential buildings in this analysis have been defined by five types, ranging from single family residences to large multifamily buildings with 20 or more units. With almost half the total building stock, 49%, single family residences are the most common building type across the Commonwealth. Additionally, 39% of residential building square footage was built prior to 1950 and 66% was built prior to 1980. Since 2000, large multifamily residential buildings have increased as a proportion of the residential stock, although are still less prevalent than single family homes.

Commercial buildings represent 23% or 1.3 billion square feet across the Commonwealth (Figure 9). Commercial buildings are diverse in their uses and are typically larger and include a broader array of end uses than residential buildings. While commercial buildings have less aggregate area compared to residential, they have significantly different occupancy patterns and needs for energy. In most cases, commercial buildings are more energy intensive than residential buildings, but are far less numerous. Decarbonization solutions for these tend to require a more site-specific design.

3.2 Growth Projections and Future Building Stock

The rates of future building development is derived from socioeconomic projections, developed by the University of Massachusetts Donahue Institute (UMDI) and MAPC for the Massachusetts Department of Transportation (MassDOT) Long-Range Transportation Plan (LRTP), included projections of population, households, and employment by municipality at decadal time-steps to 2040 (MassDOT 2018). MAPC and EEA contracted for UMDI to extend these projections to 2050 as part of their Metro Commons 2050 planning effort and this report, respectively. UMDI and MAPC developed three different growth scenarios (baseline, high-, and low-growth); only the baseline and high growth scenarios are evaluated in this report. Growth projections were generated prior to the emergence of the COVID-19 pandemic, the impacts of which, at current writing, are unknown regarding both population growth and building construction.

Mining the MAPC Land Parcel Database – a statewide repository of detailed land-use parcel data collected at the municipal level for property tax assessments, built from the MassGIS Level 3 Parcel Geodatabase and other sources — EEA staff computed average building characteristics for multiple housing typologies by community cohort.[24] These characteristics include an estimated mix of housing stock (e.g., X percent single-family, Y percent small multi-family, Z percent large multifamily) constructed since 2000, and were used to parse the housing projections from UMDI into estimates of new housing stock. In addition, EEA staff applied average size coefficients for each typology and community cohort to estimate the total square footage that a development would represent. Rather than developing a more complex methodology utilizing employment projections, project team members elected to compute average ratios of commercial square footage to residential square footage, by community cohort, in order to project commercial build-out as a function of expected residential square footage.

From 2000-2016, the Commonwealth’s building stock grew by 824 million square feet, or 16%. Growth in the Buildings Sector, defined here from 2017-2050, is forecasted to continue to grow by another 1.4 billion square feet (23%) to represent 19% of the building stock in 2050. Two growth scenarios were included in the analysis;

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[24] “Community cohorts” reflect the permutations of the 13 RPAs and five “community types” assigned semi-quantitatively to each of the 351 cities and towns in MA by MAPC. These types include:
1. Inner Core (MAPC region only); 2. Maturing Suburbs; 3. Developing Suburbs; 4. Regional Urban Centers; 5. Rural Towns
Not all permutations are represented in Massachusetts – for example there are no rural towns in the MAPC region. This approach reduces sample bias from looking at individual cities and towns, but still allows for greater differentiation than rolling up to the region level alone (e.g., while both are in the Pioneer Valley, development in Springfield is likely quite different from development in Montague).

a baseline growth projection and a high growth scenario for sensitivity based on projections from the UMDI. The baseline growth projection shows continued rapid growth from 2017-2030 and less rapid growth from 2030-2050 while the high growth scenario accelerates growth in all decades in similar trends to the baseline. As shown in Figure 9, 64% of all growth in the building stock is projected to occur by 2030.

Importantly, the projection of recent development trends continues the shift toward large multifamily residential buildings, as shown in Table 3. By 2050, the large multifamily residential cohort is projected to grow by 345 million square feet, almost 50% of existing area (708 million square feet). Specifically, the cohort of tall, large multifamily buildings (20+ family, steel construction) is expected to more than triple its area by 2050, from 20 million square feet to 69 million square feet in 2050. However, despite that growth, single family and small multifamily are still expected to be the dominant residential building types, comprising 62% of new construction by 2050.

Figure 9. Predicted New growth by Decade in the Buildings Sector Baseline Growth

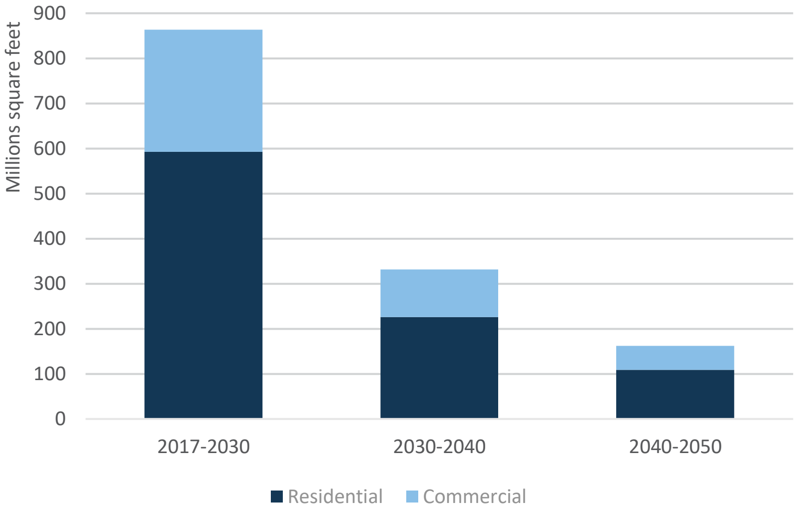


Table 3. Projected Residential Growth by Decade in the Buildings Sector

Total Building Area (Msf)	Single Family Residential	Small Multifamily Residential	Large Multifamily (5-19 family)	Large Multifamily (20+ wood)	Large Multifamily (20+ steel)
2017-2030	323	51	78	108	33
2030-2040	122	21	32	41	11
2040-2050	55	11	16	21	6
TOTAL	500	83	125	171	50
% residential growth	54%	9%	13%	18%	5%

A similar trend is forecasted in the Commercial building stock. Commercial buildings are projected to grow by 428 million square feet (32%) and to comprise 24% of the building stock in 2050. Table 4 shows the predicted commercial growth by decade in the Buildings Sector. 63% of all commercial growth in the building stock is forecasted to occur by 2030. This translates to annual growth rates of 1.41% from 2017-2030, 0.48% from 2030-2040, and 0.23% from 2040-2050. Of the 270 million square feet of growth by 2030, 38% of the growth is projected to be large office. Large office buildings are forecasted to continue to be the dominant building type, representing 39% of all building growth by 2050 or 166 million square feet.

Table 4. Projected Commercial Growth by Decade in the Buildings Sector

Total Building Area (Msf)	2017-2030	2030-2040	2040-2050	TOTAL	% of Commercial Sector Growth
Small Office	5.6	2.1	0.9	8.7	2%
Medium Office	27.5	10.6	5.1	43.2	10%
Large Office	102.8	40.7	22.1	165.6	39%
Hospital	5.3	2.1	1.1	8.6	2%
Laboratory	10.7	4.0	2.1	16.8	4%
Convention/Assembly	15.8	6.1	2.8	24.8	6%
Hotel	8.6	3.3	1.8	13.6	3%
Restaurant	4.6	1.8	0.8	7.2	2%
Retail	47.3	18.3	8.7	74.3	17%
K-12 School	3.2	1.2	0.5	4.9	1%
Supermarket	2.2	0.9	0.4	3.5	1%
Warehouse	36.7	14.2	6.4	57.3	13%
TOTAL	270.4	105.3	52.7	428.4	

High Growth Scenario

Under the High Growth scenario, the building stock increases from 5.9 billion square feet in 2017 to 7.2 billion square feet in 2030 (16% increase) and 7.8 billion square feet in 2050, an overall increase of 33% in the building stock. Table 5 shows the forecasted growth by decade in the Buildings Sector under this scenario. New construction would represent 25% of building stock in 2050, compared to 19% in the baseline growth scenario. In aggregate, this represents an addition of approximately 600 million square feet from 2017-2050 (413 million residential square feet and 187 million commercial square feet).

Table 5. Projected Growth by Decade in the Buildings Sector – High Growth Scenario

Total Building Area (Msf)	Residential	Commercial	Total
2017-2030	899	410	1,309
2030-2040	303	140	443
2040-2050	139	65	204
TOTAL	1,341	615	1,956
% growth	69%	31%	

At the time of the writing of this report, the COVID-19 pandemic is still unfolding. The growth assumptions used above were defined in 2008-2019 prior to the start of the pandemic. The long-term effects of the pandemic are not yet clear, but there are potential implications to the building stock moving forward. These implications could include changes to codes and standards for ventilation and air filtration, overall construction activity, changes in the anticipated demand of different building types (e.g. fewer office buildings constructed), need for new building space (e.g. additional school buildings). The analysis has used growth projections that were based on the best available assumptions at the time, but it is recognized these are likely to change given disruptors, such as the current pandemic.

Residential Buildings

The high growth scenario shows similar growth trends in the residential building stock, shown in Figure 10 and Figure 11. Residential building area increases to from 4.33 Billion square feet in 2017 to 5.2 billion square feet in 2030, a 21% increase to 5.7 billion square feet in 2050 in the high growth scenario, an increase of 31%. New residential square footage would represent 24% of the residential building stock.

Figure 10. Residential Building Square Footage 2017-2050 by Baseline and High Growth Scenarios

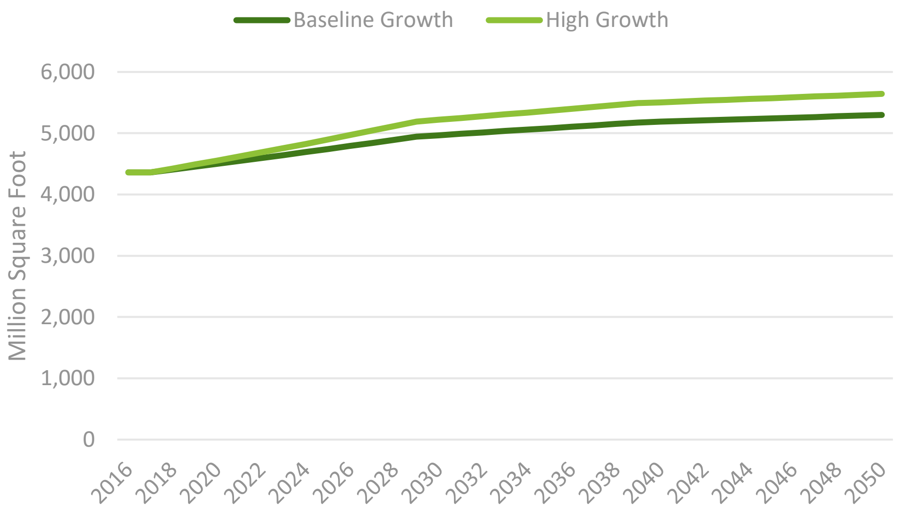
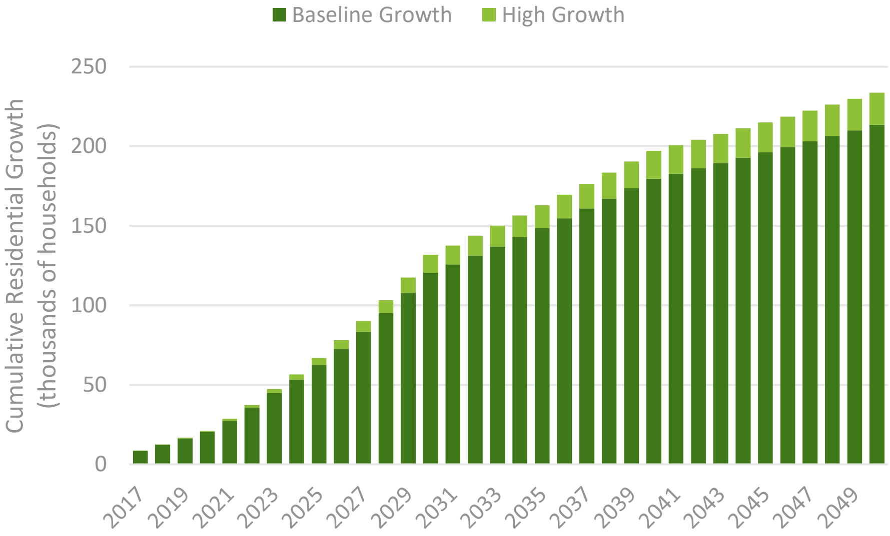


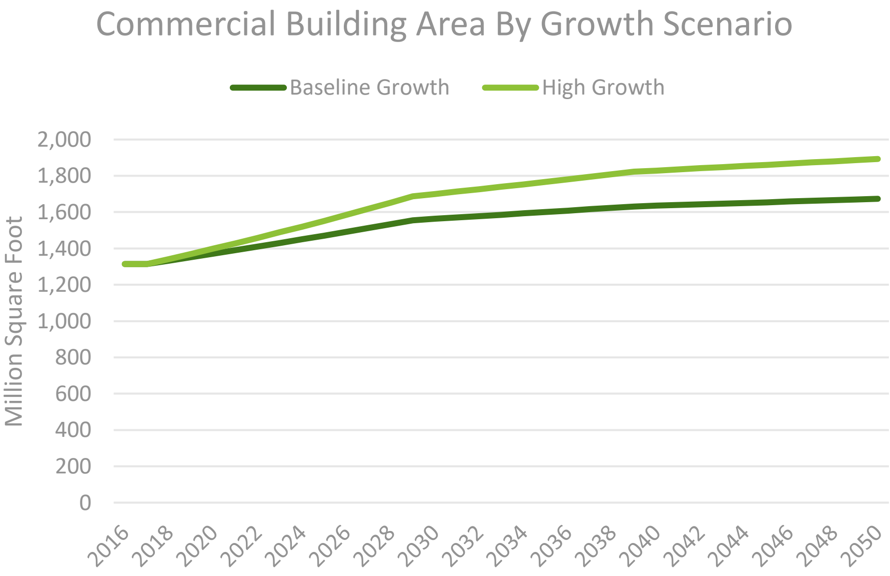
Figure 11. Cumulative growth in residential households 2017-2050 by baseline and high growth scenarios



Commercial Buildings

The high growth scenario forecasts similar accelerated growth trends in the commercial building stock as it did in the residential. Commercial building area increases from 1.3 billion square feet in 2017 to 1.7 billion square feet in 2030, a 31% increase, and to 1.9 billion square feet in 2050 in the high growth scenario (Figure 12). New commercial square footage would represent 32% of the commercial building stock and 25% of the combined commercial and residential building stock in 2050.

Figure 12. Commercial Building Square Feet 2017-2050 by Baseline and High Growth Scenarios



3.3 Building Energy Modeling Methodology

This study developed a bottom-up energy model of the Commonwealth's existing building stock that included (18) typologies and (3-5) vintages. Detailed energy models representing this cross-section of Massachusetts' building stock were scaled up using detailed square footage data to form a basis for modeling the energy consumption of the Commonwealth. Both the Commonwealth-wide energy results as well as individual model results were calibrated using a combination of benchmarking data and utility data to construct a relatively accurate representation of Massachusetts' building energy consumption. This calibrated energy model formed the basis for testing the energy conservation measures outlined in this report. The following workflow was implemented using a combination of EnergyPlus models, custom Python scripts for mass-editing the models and processing results, and cloud-simulation services for handling the simulations at scale.

3.3.1 **EnergyPlus Models**

Creating realistic energy models for each typology required determining the key assumptions that drive each of the 18 buildings' energy consumption. As a starting point, residential and commercial building models from the United States Department of Energy's (DOE) prototype repository were used; the climate zone 5A models were used, as this is the climate zone that most broadly represents Massachusetts. These models were developed for 18 building types using characteristics that represent approximately 70% of the building stock within the US.[25] Where a DOE prototype models existed that matched the required vintages the model was used, otherwise the closest model was duplicated to be edited based on the assumptions listed in Table 6.

For the purposes of this study, 15 of the DOE prototype models were a direct match. However, 3 typologies were not represented and custom EnergyPlus models were needed to be created with prototype model assumptions forming the basis for creation where applicable. Additionally, within the DOE models, the provided prototype vintages align closely with the 1950-1980, 1980-2000, and Post-2000 categories used in this study. However, additional models were created for the Pre-1950 vintage. For typologies that had a matching prototype model, the geometry of the building was held constant to allow for a more accurate inter-vintage comparison of energy performance.

After aggregating applicable prototype models and creating bespoke models where necessary, the model inputs were edited to better-reflect the characteristics of buildings in Massachusetts. Inputs were used from the Commercial Buildings Energy Consumption Survey (CBECS),[26] the Residential Energy Consumption Survey (RECS),[27] the Manufacturing Energy Consumption Survey (MECS),[28] and the State Energy Data System (SEDS).[29] The aforementioned sources are national surveys by the US Energy Information Administration (EIA) that collect building characteristics and energy use data from the United States building stock. Where region- or

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[25] Department of Energy: Office of Energy Efficiency and Renewable Energy. *Commercial Reference Buildings*. https://www.energy.gov/eere/buildings/commercial-reference-buildings

[26] U.S. Energy Information Administration. Commercial Buildings Energy Consumption Survey (CBECS). *2018 Commercial Buildings Energy Consumption Survey Preliminary Results.* 2020. https://www.eia.gov/consumption/commercial/

[27] U.S. Energy Information Administration. *Residential Energy Consumption Survey (RECS).* 2020. https://www.eia.gov/consumption/residential/

[28] U.S. Energy Information Administration. *Manufacturing Energy Consumption Survey (MECS).* 2018. https://www.eia.gov/consumption/manufacturing/

[29] U.S. Energy Information Administration. *The State Energy Data System.* 2019. https://www.eia.gov/state/seds/

state-specific data were available, the most granular level of available data was incorporated into the model. Data sources are summarized in Table 6 and Table 7.

Table 6. Mapping of DOE prototype models to those used in this study.

Project Building Typology	DOE Prototype Building Typology[30,31,32]
Single Family Residential	Single-family detached
Small Multifamily Residential	Multi-family low-rise apartment building
Large Multifamily Residential (5-19 Stories)	Mid-rise Apartment
Large Multifamily Residential (Wood Construction) (20+ Stories)	High-rise Apartment
Large Multifamily Residential (Wood Construction) (20+ Stories)	High-rise Apartment
Office Small	Small Office
Office Medium	Medium Office
Office Large	Large Office
Hospital	Hospital
Laboratory	See Section IV.I.II.I
Convention/Assembly	See Section IV.I.II.II
Hotel	Large Hotel
Restaurant	Full-Service Restaurant
Retail	Strip Mall
K-12 School	Secondary School
Supermarket	Supermarket
Warehouse	Warehouse (non-refrigerated)

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[30] https://www.energycodes.gov/development/residential/iecc_models

[31] U.S. Department of Energy. *Building Energy Codes Program*. 2018. https://www.energycodes.gov/development/commercial/prototype_models#:~:text=Development-,Commercial%20Prototype%20Building%20Models,model%20codes%20and%20potential%20changes.

[32] Department of Energy: Office of Energy Efficiency and Renewable Energy. *Commercial Reference Buildings*. https://www.energy.gov/eere/buildings/commercial-reference-buildings

Table 7. Correlated vintages for DOE prototype models vs. study.

Project Vintage	DOE Prototype Building Vintage
Pre-1950s	N/A
1950-1980	Pre-1980
1980-2000	Post-1980
Post-2000	New Construction

The laboratory reference model was created using internal gains templates found within the Hospital DOE prototype model (which included laboratory templates), however these internal gains categories were reapportioned to represent an area allocation consistent with laboratory projects previously designed by the team. Furthermore, airflows were adjusted to reflect the higher ventilation demand of laboratory fume hoods and associated systems.

The convention/assembly reference model was derived from the large office reference model's geometry, as this typology is meant to represent the mixed-use typology common in Massachusetts' urban centers. This typology uses templates and HVAC strategies based on those developed for the Carbon Free Boston (CFB) Buildings Report[33] were then applied to this geometry in a similar proportion to CFB. This approach blended a warehouse structure, with systems and internal gains representative of small offices, and process loads inclusive of restaurants.

3.3.2 **Model Calibration**

Inputs from nationally-aggregated data sources and DOE prototype models provide a good starting point for Commonwealth-wide modeling. However, to more accurately reflect the current state of the building sector within Massachusetts, statewide utility data from Eversource, National Grid, and Columbia Gas were aggregated for the purpose of better-aligning annual, monthly, and peak profiles across the Commonwealth. The three utilities cover approximately 90% of the Commonwealth. Because this data does not reflect all the energy consumed within the Commonwealth, the utility data was used to proportionally allocate the fuel consumption reported by the EIA surveys.

For each utility dataset, the monthly totals, the monthly peak demand, and the time of day the peak occurred were given, and the hourly electricity data were aggregated from ISO New England[34] to cross-check hourly profiles against the monthly profiles provided by the utilities.

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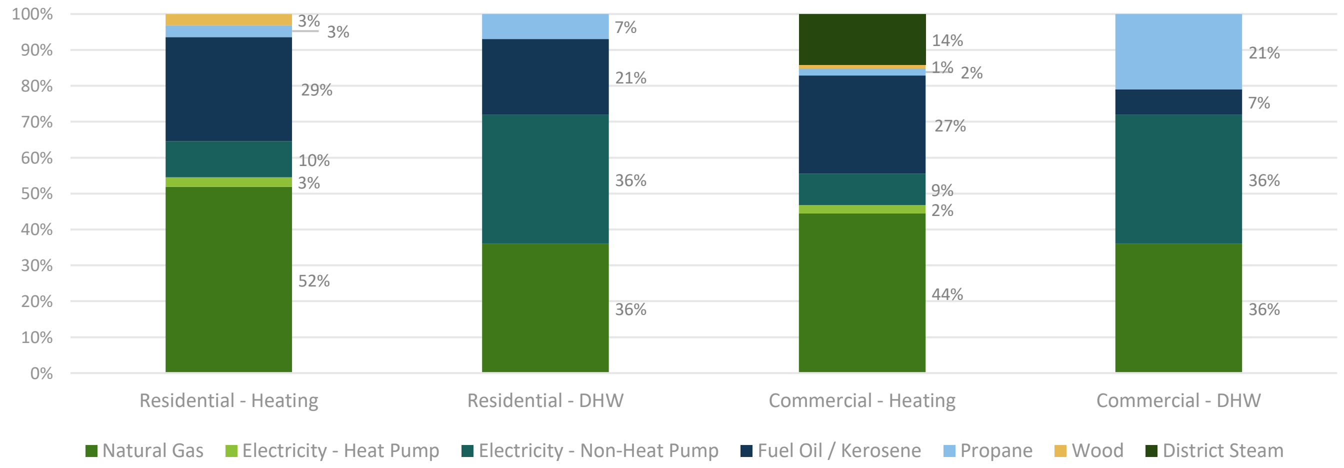
[33] Boston University Institute for Sustainable Energy – Carbon Free Boston – Technical Reports. http://sites.bu.edu/cfb/carbon-free-boston-report-released/technical-reports/

[34] ISO New England. *Real Time Maps and Charts.* 2020. https://www.iso-ne.com/isoexpress/web/charts

Before calibrating to Commonwealth-wide data, each typology was aligned with BERDO[35], BEUDO[36], EIA[37] and EnergyStar[38] benchmarks. Once aligned, the area-normalized energy profile of each typology was multiplied by the fuel breakdown for each end-use (as shown in Figure 13) and by the Commonwealth-wide area segmentation for each typology to yield the aggregated fuel use for Massachusetts. This fuel use was then aggregated into monthly profiles and measured against the known consumption data using the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) tests as described below.

Figure 13. Residential and commercial fuel allocation per BTU of space heating and domestic hot water use.



NMBE tests if there is a continuous over- or under-estimation of energy performance within the model. NMBE is calculated as follows:

$$\boldsymbol{B_{NMB} = \frac{1}{m} \cdot \frac{\sum_{i=1}^{N}(m_i - s_i)}{n - p} \times 100\%}$$

CV(RMSE) test if the magnitude of difference between the modeled and observed data is significant. CV(RMSE) is calculated as follows:

$$\boldsymbol{CV_{RMSE} = \frac{1}{m} \cdot \sqrt{\frac{\sum_{i=1}^{N}(m_i - s_i)^2}{n - p}} \times 100\%}$$

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[35] https://data.boston.gov/dataset/building-energy-reporting-and-disclosure-ordinance

[36] Analyze Boston. *Building Energy Reporting and Disclosure Ordinance (BERDO).* 2020. https://www.cambridgema.gov/CDD/zoninganddevelopment/sustainablebldgs/buildingenergydisclosureordinance.aspx

[37] https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ma.pdf

[38] U.S. Energy Information Administration. *Household Energy Use In Massachusetts.* 2009. https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf

Academic studies using utility data to calibrate representative (rather than as-built) models have determined that NMBE values of approximately 20% and CV(RSME) of 55% for monthly data are good fits and are significantly better than uncalibrated models.[39,40]

After 23 iterations, the calibration effort yielded an NMBE of 22% and a CV(RSME) of 24% and the model was determined to be calibrated to a sufficient level for moving forward with the analysis. The parameters that were adjusted to calibrate the models generally pertained to residential and small commercial building infiltration, commercial plug loads, and the heating/DHW energy associated with labs and hospitals.

Though the model was considered calibrated enough to be used for the purposes of analysis, there was still an energy shortfall in terms of overall energy use. Rather than artificially increase the energy use of any specific typology in a way that would throw building-level targets off of their individual benchmarks, the energy shortfall was accounted for as an “other” category in the sector-wide accounting approach described below. This energy consumption is most likely the result of specific high-energy building typologies such as car washes that were not captured in the level of granularity of our segmentation.

3.3.3 Cost Assumptions

Estimated construction costs were developed for each Energy Conservation Measure (ECM, further discussed in 4.1) package to enable analysis of cost effectiveness in conjunction with energy and emissions reduction effectiveness. A total costing approach was used to aggregate the costs of the individual measures for building envelope, systems and equipment within the ECM package, specific to residential and commercial construction and commercial use type and summed to represent the total ‘cost’ of the ECM package (Table 8). The approach was not an incremental approach which alternately would define the additional cost to implement the ECM package compared to a replacement in-kind.

Multiple local and national sources were used in developing cost estimates. Local data sources within the Commonwealth were prioritized as being the most relevant and National sources were used for comparative purposes or to fill gaps as required. Specifically, the following sources were used:

- Building envelope related energy conservation measures utilized Carbon Free Boston Buildings Technical Report[41], One City Built to Last Technical Working Group Report[42], and the DOE Scout tool[43].
- Building systems related energy conservation measures utilized studies from the Northeast Energy Efficiency Partnerships (NEEP)[44], Navigant on behalf of the Electric and Gas Program Administrators of

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[39] J. Sokol, C. Cerezo Davila, and C. F. Reinhart, “Validation of a Bayesian-based method for defining residential archetypes in urban building energy models,” Energy and Buildings, vol. 134, pp. 11–24, Jan. 2017.

[40] R. Sevlian and R. Rajagopal, “Value of aggregation in smart grids,” in 2013 IEEE International Conference on Smart Grid Communications (SmartGridComm), 2013, pp. 714–719.

[41] Boston University. *Buildings Technical Report.* 2019. http://sites.bu.edu/cfb/files/2019/06/CFB_Buildings_Technical_Report_061719.pdf

[42] City of New York. *One City Built to Last Technical Working Group Report*. 2014. https://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/TWGreport_04212016.pdf

[43] Department of Energy: Office of Energy Efficiency and Renewable Energy. *Scout.* https://www.energy.gov/eere/buildings/scout

[44] New England Energy Partnerships, “Northeast/Mid Atlantic Air Source Heat Pump Market Strategies Report,” January 2014 and January 2017 reports.

Massachusetts Part of the Residential Evaluation Program Area[45], Carbon Free Boston Buildings Sector Technical Report, One City Built to Last Technical Working Group Report, and local cost estimates.

- Ground Source Heat Pump estimates used US Department of Energy technical report on GHSP deployment[46] and local cost estimates.

Table 8. Total costs of applied ECM packages.

	ECM1	ECM2	ECM3	ECM4
Single Family	$3.01	$15.16	$18.96	$22.26
Small Multifamily	$7.23	$20.58	$29.53	$34.92
Large MF 5-19	$9.40	$23.78	$27.72	$30.41
Large MF 20+ wood	$11.60	$30.56	$34.06	$39.40
Large MF 20+ steel	$11.69	$28.38	$35.99	$42.21
Small Office	$11.99	$31.57	$38.37	$44.29
Medium Office	$11.99	$25.19	$34.30	$39.63
Retail	$11.99	$32.81	$35.09	$39.88
Supermarket	$11.99	$28.41	$30.96	$34.93
Convention/Assembly	$11.81	$21.97	$27.76	$31.35
Office Large	$11.81	$20.97	$28.57	$32.51
School (K-12)	$12.04	$24.09	$30.52	$34.85
Hospital	$19.28	$24.28	$26.99	$28.13
Laboratory	$19.34	$24.34	$26.86	$28.00
Hotel	$13.11	$26.51	$32.37	$36.35
Restaurant	$15.37	$35.34	$40.75	$45.86
Warehouse	$11.99	$34.50	$34.93	$39.10

3.4 Sector Wide Synthesis

The Low Emissions Analysis Platform (LEAP)[47] is used here for sector-wide accounting. LEAP is a scenario-based integrated energy system accounting tool used for energy planning and GHG mitigation assessments at the local, state and national scale. The building segmentation and forecasts were implemented in LEAP's data structure. Output from the EnergyPlus building energy models were automatically fed into LEAP using a custom Python script to create representative baseline and retrofitted buildings representations in LEAP. Scenarios reflecting alternative adoption rates of building retrofits and new building codes were implemented in LEAP to assess the greenhouse gas and energy demand impacts of different timelines and degrees of building decarbonization strategies.

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[45] Navigant reports, "Ductless Mini-Split Heat Pump Cost Study (RES 28)," October 2018 and "Water Heating, Boiler and Furnace Cost Study (RES 19)," April 2018.

[46] U.S Department of Energy Office of Scientific and Technical Information Technical Report, "Measuring the Costs & Benefits of Nationwide Geothermal Heat Deployment"

[47] Low Emissions Analysis Platform (LEAP). https://leap.sei.org/default.asp?action=introduction

4 New Buildings

Buildings constructed following the publication of this report are anticipated to comprise 19% of the building stock in 2050. While any building built today will be more energy efficient than the average existing stock, without changes in practices, new construction buildings will be predominantly built to use fossil fuel-consuming equipment that will still be in operation in 2050. Newly constructed, high performing buildings that are all electric avoid the lock-in of fossil fuel systems and avoid needing an expensive retrofit or decarbonized fuel to achieve future decarbonization targets. Such buildings can be designed and constructed today with little additional cost compared to fossil fuel-using buildings. High performance refers to the building envelope and systems that facilitates very low energy consumption. Mixed fuel buildings that use electricity and decarbonized gas were not evaluated here. We focused our analysis on the implementation of electric systems. High performing buildings with zero site emissions are often referred to as *Net-Zero Emissions* buildings if zero-carbon electricity supplies are used to power the building. If such electricity was produced on site to meet the demand of the building, such a building is often termed a *Net-Zero Energy* building. Given efforts to significantly decarbonize electricity supplies, the off-site accounting of emissions is not focus of this study.

Although new buildings represent a fraction of future emissions in this sector, early action on new construction can accelerate the decarbonization of existing buildings. Such action codifies innovation, encouraging the adoption of design and technologies that might not otherwise be adopted. This increases consumer and contractor familiarity with all electric technologies, which can accelerate their diffusion into the existing building stock.[48]

Since the establishment of the building energy code, generally each generation of buildings has been more efficient than the previous; this improvement has been realized through design and technological advancements. The existence of building energy codes requires that a minimum level of these design and technological advancements are widely adopted. Historically, the code has focused on reducing energy demand to ensure that operating the building is cost effective for the owner or occupant, and to ensure that energy distribution systems do not become overtaxed and require costly upgrades that are borne by other ratepayers. To align with decarbonization goals, the code should focus not only on energy but on emissions reductions, and more directly fuel switching in addition to energy efficiency, with such focus being implemented on a timeline consistent with the Commonwealth’s decarbonization goals.

The Massachusetts Department of Energy Resources (DOER) is conducting a comprehensive assessment of new commercial building energy performance consistent with the Commonwealth’s Net Zero 2050 limit. This assessment is intended to evaluate the cost and energy tradeoffs associated with different levels of building performance. The analysis will inform the update to the 2021 stretch code. The work presented herein is intended to provide a high-level contextualization of the impacts of the timing and depth of code implementation.

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[48] Massachusetts Energy Efficiency Advisory Council. 2018. http://ma-eeac.org/wordpress/wp-content/uploads/TXC_48_RNCAttribution_24AUG2018_Final.pdf

4.1 New Buildings Performance Levels

Two advanced versions of new construction buildings were defined for this study to understand the range of potential new building energy use. The two versions, defined for the analysis to include varying levels of energy efficiency, both assume the effective elimination of on-site combustion.

4.1.1 Net Zero

For the purposes of this analysis, Net Zero new construction is defined as being consistent with the electrification and deep efficiency benchmarks described in the All Options pathway, discussed in the *Energy Pathways Report* – that is, that the new construction is compatible, as-built, with the Commonwealth's net-zero emissions economy in 2050*.* Its focus is on-site emissions; it does not necessitate onsite or offsite renewables, nor the assumption that a building is net-zero energy.

Assumptions surrounding Net Zero new construction are applicable and are applied in this analysis to all residential and commercial building types. These assumptions include enhanced energy efficiency compared to current code and effective elimination of on-site emissions from space heating, domestic hot water, cooking and other process uses. It is approximately comparable to the Zero Emissions Building Code that has been in place in Vancouver, British Columbia, since 2016.

4.1.2 Passive House

Passive House is a certification scheme for buildings that focuses on ultra-high energy efficiency, predominantly driven by a highly efficient building envelope to reduce the need for mechanical systems. It is a performance-based certification based on three criteria; ultra-low air infiltration rate, a source energy use intensity (EUI) limit, and space conditioning criteria defined as maximum values for annual heating and cooling demand and heating and cooling peak demand. Aside from using source EUI, the standard in its current version does not specify the building be all electric. As such, Passive House certified buildings can utilize natural gas or electricity.

For the purposes of this analysis, only residential buildings (all 5 typologies) were included in the passive house analysis, since this is the most common application of the standard. Additionally, the Passive House buildings were defined to be all-electric using air source heat pumps for heating and domestic hot water end uses and electric induction cooking. The Passive House analysis was included to test the sensitivity and quantify the value of additional energy efficiency in residential buildings and all-electric new construction for its impact on further GHG emissions reduction.

4.1.3 Performance Levels

Net Zero and Passive House standards for new construction can have a significant impact on energy efficiency and GHG emissions as both options are all electric (Table 9).

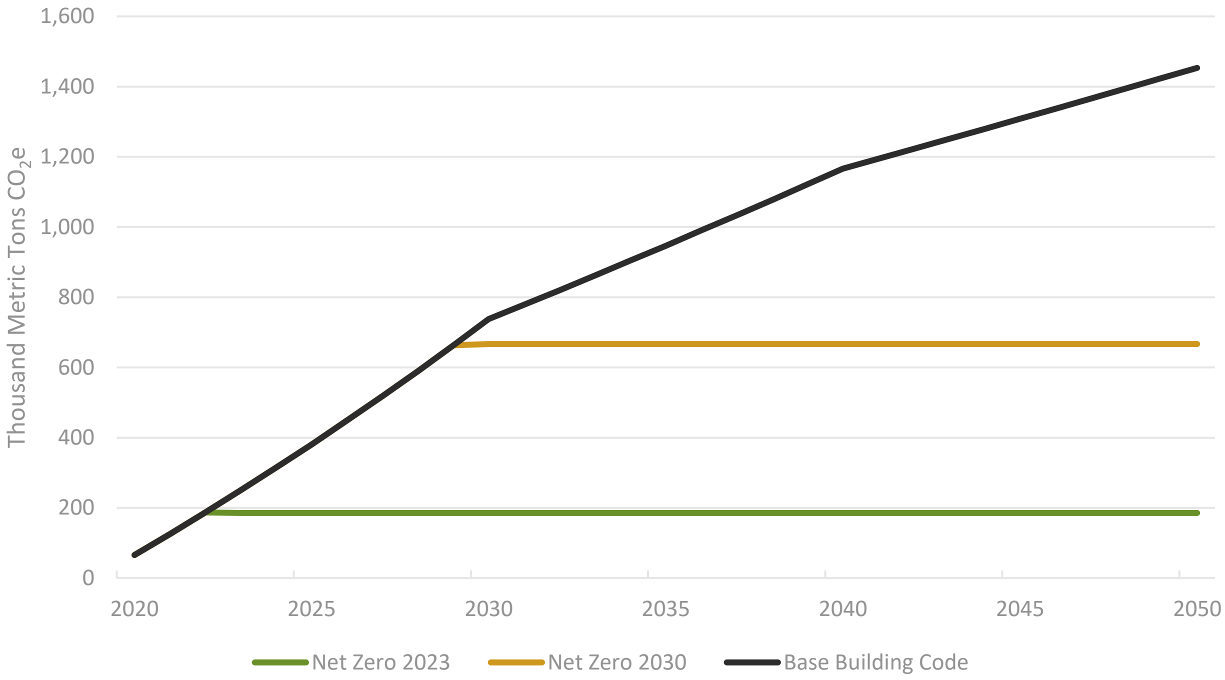
Table 9. Change in Energy Use Intensity by Building Type under New Construction, Net Zero, and Passive House scenarios

Energy Use Intensity (kBtu/sf/year)	New Construction (Current Code)	Net Zero	% reduction	Passive House	% reduction
Single Family Residential	32	13	59%	12	63%
Small Multifamily Residential (2-4 family)	67	19	72%	14	79%
Large Multifamily Residential (5-19 family)	40	16	60%	14	66%
Large Multifamily Residential (20+ wood)	56	34	40%	29	48%
Large Multifamily Residential (20+ steel)	57	36	37%	33	43%
Small Office	23	20	12%	-	-
Medium Office	32	25	21%	-	-
Large Office	68	63	8%	-	-
Hospital	110	54	51%	-	-
Laboratory	153	128	17%	-	-
Convention/Assembly	63	53	17%	-	-
Hotel	71	31	57%	-	-
Restaurant	120	94	22%	-	-
Retail	113	90	20%	-	-
K-12 School	90	62	31%	-	-
Supermarket	361	231	36%	-	-
Warehouse	162	92	43%	-	-

4.2 Timing of New Building Codes

Assuming a continued, historical pace of advancement of the building code to 2050 without the implementation of a zero-site emissions policy earlier, emissions from new buildings are anticipated to grow to nearly 1.5 MMT CO_2 by 2050 (Figure 14). The adoption of a high-performance (the equivalent of Net Zero or Passive House examined here) new construction code would reduce annual 2050 emissions from residential and commercial new construction by 0.8 MMT CO_2 (54% reduction) if implemented in 2030 and by 1.30 MMT CO_2 (87% reduction) if implemented in 2023. Total emissions saved over 30 years reach 22 MMT CO_2 by 2050 if this code is implemented in 2023 and 10 MMT CO_2 if implemented in 2030. The additional 12 MMT CO_2 in cumulative savings resulting from advancing the code seven years highlights the impact of immediate action in avoiding the lock-in of fossil fuel technologies.

Figure 14. Annual emissions from new construction associated with a 2023 and 2030 implementation of a high-performance electric code, as well as a no implementation scenario for commercial and residential buildings. Note that this does not include forecasts of unclassified energy-demand currently serviced by natural gas.



5 Existing Buildings Electrification & Efficiency Retrofits

Despite the new construction results detailed above, even by 2050, structures that exist today will still represent over 80% of the total building stock. Addressing these existing buildings is central to the meeting the decarbonization targets of the Commonwealth. Renovating existing buildings of any type, residential or commercial faces several barriers not experienced by new construction. First building system lifecycles are long, with HVAC systems often reaching 15-30 years and building envelopes exceeding 40. Second, replacement of HVAC is usually like-for-like during emergency replacement at end-of-life failure. It is thus imperative to know the level of action needed to electrify and reduce energy use in buildings and in which buildings those opportunities lie. This section evaluates the application of electrification and efficiency measures to representative building types in Massachusetts.

5.1 Decarbonization through Energy Conservation Measure (ECM) Packages

The aim of this study is to understand how much decarbonization in the building sector can be achieved through electrification and fuel switching building systems alone, and how much building envelope improvements will be needed to support decarbonization. While the *Energy Pathways Report* evaluates the energy cost and resource impacts associated with pursuing or deferring end-use energy efficiency and electrification, it does so a high level. This study builds off of that work to take a more granular, building- and intervention-level approach to building decarbonization. As such, a series of energy conservation measure (ECM) packages ECM packages were developed that were based on technology that exists today. These ECM packages were designed to holistically electrify the building sector, with varying degrees of energy efficiency. A systems-only starting point based largely on the adoption of air-source heat pumps (ASHP)—ECM 1—was devised to be a first step towards electrification. ASHPs were determined to be the most common means for electrifying space and hot water heating given the dramatic low-temperature performance advancements in recent years. A ground-source heat pump (GSHP) version of this package is also evaluated. ECM packages 2 – 4 were designed to introduce progressively rigorous envelope and system improvements. By staging ECM packages in this progressive manner, it allowed the team to test various combinations of interventions while limiting consumer effort and cost rather than evaluate piecemeal ECMs. A summary of each ECM package is listed immediately below. Detailed parameters for the ECM packages are presented in Appendix B: Detailed Description of ECM Packages.

5.1.1 **ECM 1 – Entry-Level Efficiency: Systems & Equipment Only**

The ECM packages studied were designed to layer approaches that exist in the market today on top of one another towards the goal of a decarbonized Commonwealth. ECM 1 is the foundational layer and results in the electrification of space heating and domestic hot water heating, providing a necessary step towards enabling decarbonization via electrification and increasingly low carbon electricity supplies. It involves the simplest intervention for consumers. Because of the difference of scale involved with small residential and all other typologies studied, ECM 1 manifests slightly differently depending on typology. At a high level, the interventions associated with ECM 1 are described in Table 10.

Table 10. Summary description of ECM 1.

Category	Small Residential	Large Residential + Commercial
Systems	Heat pump electrification of space heating and DHW	Heat pump electrification of space heating and DHW
Envelope	None	None
Controls	Thermostat setbacks	Thermostat setbacks, demand-control ventilation, energy recovery
Appliances	Replacement with electric alternatives	Replacement with electric alternatives

5.1.2 ECM 2 – Medium Efficiency: Systems & Equipment and Limited Envelope

Electrifying the state's building stock will couple building emission footprints with an ever-improving electricity grid, which provides a path towards decarbonization. However, electrically heating structures with inefficient envelopes has the potential to put excessive demands on the electrical grid at both local and regional scales (see *Energy Pathways Report*). Envelope interventions aimed at minimizing seasonal and peak heating demands were layered on top of the electrification efforts of ECM 1. Furthermore, in many residential buildings, envelope infiltration is the only means for providing ventilation to occupants. As such, a more efficient ventilation system was included to provide a new path for fresh air to avoid unintended health consequences from air-sealing the building envelope. Table 11 outlines the interventions made under ECM 2.

Table 11. Summary description of ECM 2.

Category	Small Residential	Large Residential + Commercial
Systems	ECM 1 systems	ECM 1 systems
Envelope	Improved roof and wall insulation + improved airtightness	Improved roof and wall insulation + improved airtightness
Controls	Demand-control ventilation, energy recovery	ECM 1 controls
Appliances	ECM 1 appliances	ECM 1 appliances

5.1.3 ECM 3 – High Efficiency: Systems & Equipment and Envelope

With ECM 1 providing an electrified path towards long-term decarbonization, and ECM 2 minimizing the burden on the consumer's electricity bills as well as the electricity grid, ECM 3 provides an additional layer of envelope and system-level efficiency. Table 12 outlines where ECM 3 makes improvements on top of the interventions outlined in ECM packages 1 and 2.

Table 12. Summary description of ECM 3.

Category	Small Residential	Large Residential + Commercial
Systems	High-end heat pump electrification of space heating and DHW	High-end heat pump electrification of space heating and DHW
Envelope	Double-pane windows + above-code airtightness + ECM 2 envelope	Double-pane windows + above-code airtightness + ECM 2 envelope
Controls	ECM 2 controls	ECM 1 controls
Appliances	ECM 1 appliances	ECM 1 appliances

5.1.4 ECM 4 – Highest Efficiency: Systems & Equipment and Envelope

Just like ECM 3, ECM 4 provides an additional layer of efficiency on top of what is specified in ECM packages 1 and 2. However, ECM 4 goes further than ECM 3 and represents a best-in-class intervention for existing buildings undergoing a deep energy retrofit. Table 13 outlines where ECM 4 goes above and beyond ECM packages 1, 2 and 3.

Table 13. Summary description of ECM 4.

Category	Small Residential	Large Residential + Commercial
Systems	Best-in-class heat pump electrification of space heating and DHW	Best-in-class heat pump electrification of space heating and DHW
Envelope	Above-code wall insulation + triple-pane windows + Passive House airtightness + ECM 3 envelope	Above-code roof and wall insulation + triple-pane windows + Passive House airtightness + ECM 3 envelope
Controls	ECM 2 controls	ECM 1 controls
Appliances	ECM 1 appliances	ECM 1 appliances

5.1.5 Additional Considerations

While there will likely be innovations in the next 30 years that make achieving deep decarbonization easier, it was important for the project to plan around technologies that are available now to demonstrate that action can be taken today. As such, ECM packages actions that don't involve system electrification, that only position the building stock to await a future innovations and distribution scale-ups in alternative fuel sources were not considered as a part of the illustrative pathways outlined in this study.

Furthermore, though air conditioning is not necessarily present in every household in Massachusetts today,[49] the climate in 2050 is likely to require air conditioning to be installed in nearly every household. Thermally insulated envelopes that are of great benefit when retaining heat in the winter but can exacerbate indoor heat stresses in the summer without an air conditioning system. Given this, an air conditioning system will

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[49] U.S. Energy Information Administration. Residential Energy Consumption Survey (RECS). Table HC 7.7.https://www.eia.gov/consumption/residential/data/2015/hc/php/hc7.7.php

eventually be needed to be installed in conjunction with a more thermally resistive envelope. Given that heat pumps can produce air conditioning as well as heating, a solution that satisfies both a need for efficient air conditioning and efficient heating without equipment duplication served as a basis for constructing the ECM packages.

For illustrative purposes, in some of the building analyses below, derivative packages are used to show comparative impacts of technologies that will likely play a secondary role to air source heat pumps. These include ground source heat pumps, decarbonized gas, and electric resistance heaters.

5.2 Building-Level Results

Key highlights for the main composite typologies (as defined in Table 1) are presented in the following sections. The results of the Single-Family typology are discussed in detail below, with a focus on the pre-1950 vintage. The general impacts of electrification and efficiency covered by this typology are applicable to other typologies. Additional typologies are presented in subsequent sections, with some additional typology-specific context.

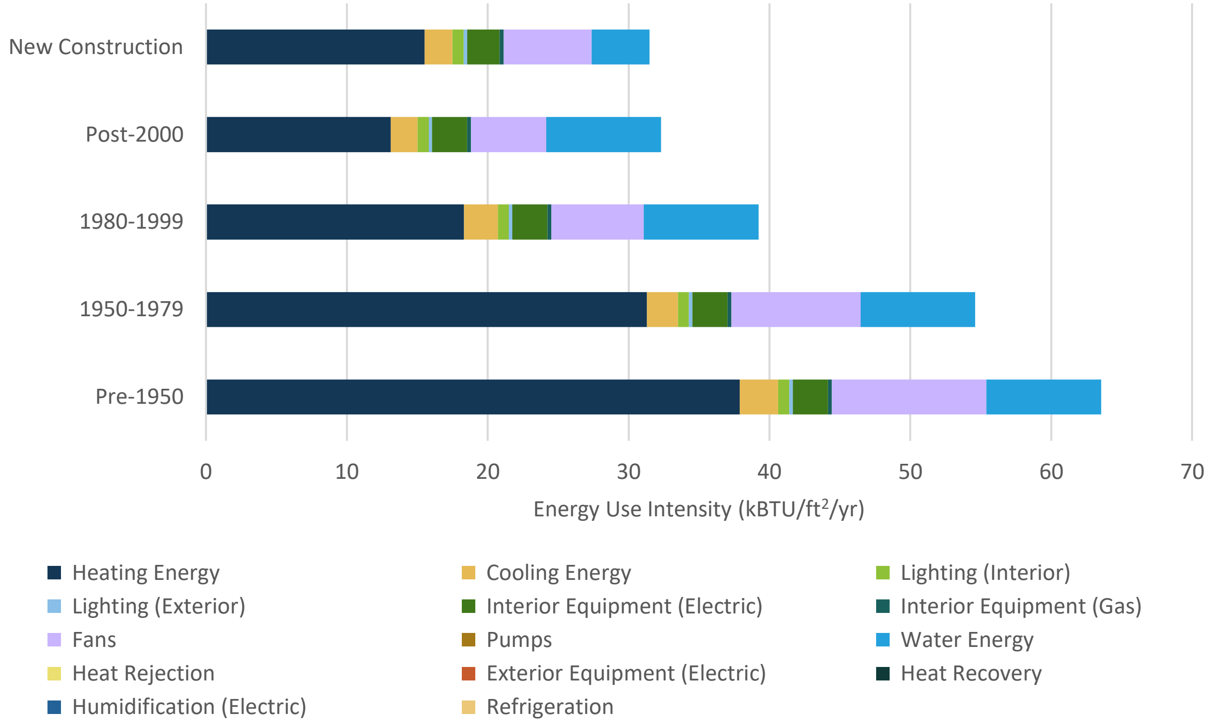
5.2.1 **Single Family**

5.2.1.1 Building Stock Summary

Single-family homes have a greater share of built square footage than any other typology in the Commonwealth, totaling over 2.8 billion ft^2 of the Commonwealth's total 5.8 billion ft^2. This single-family square footage comprises 1.42 million households in total. Within the single-family typology, over 60% of the building stock was built before 1980.

This large number of pre-1980s buildings is significant to the decarbonization effort, because energy use in the single-family residential typology can be characterized by large space and water heating demands, with pre-1980s homes consuming more than double the amount of heating energy used by newer buildings (Figure 15). This is largely driven by leaky envelopes with high outside air infiltration, inefficient fossil fuel-burning heating equipment, lower levels of envelope insultation, and limited controls.

Figure 15. Energy use intensity for reference Single Family Residential vintages. Fans represent forced air for heating and cooling.

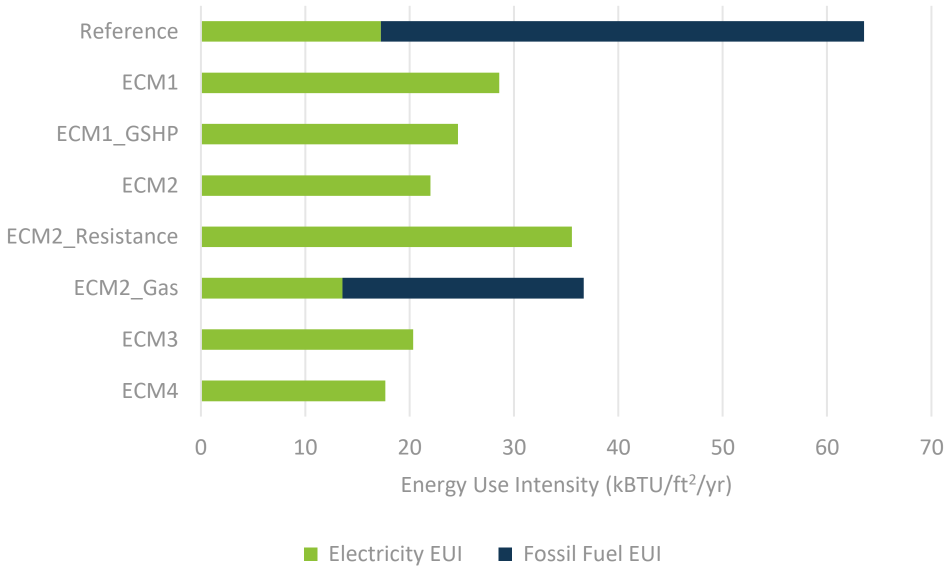


5.2.1.2 ECM Impacts: Aggregate Demand

Figure 16 shows the overall impact on aggregate annual energy use following the application of the ECM packaged described above to a Pre-1950 single family home prototype. Notably, electrification (conversion from Reference to ECM1) results in the elimination of natural gas but a 66% increase in electricity use relative to the baseline. However, electrification of heating, hot water, and cooking leads to a significant overall reduction in energy use, greater than 50% compared to the baseline.

Low cost and minimally disruptive insulation to walls and roofs and weather stripping to reduce air infiltration (ECM2 – Mass Save Package) are able to deliver an 18% reduction in energy use after electrification and associated energy efficiency, while a deep energy retrofit with the highest performing systems available today (ECM4) is able to double that savings and deliver a 38% benefit. The modeled ECM packages had a far greater impact on older homes than newer homes. This suggests that older single-family residential homes have a larger technical potential for efficiency and emissions reduction. This is further discussed below in Section 5.2. Box 1 discusses the impact of the ECM packages on emissions.

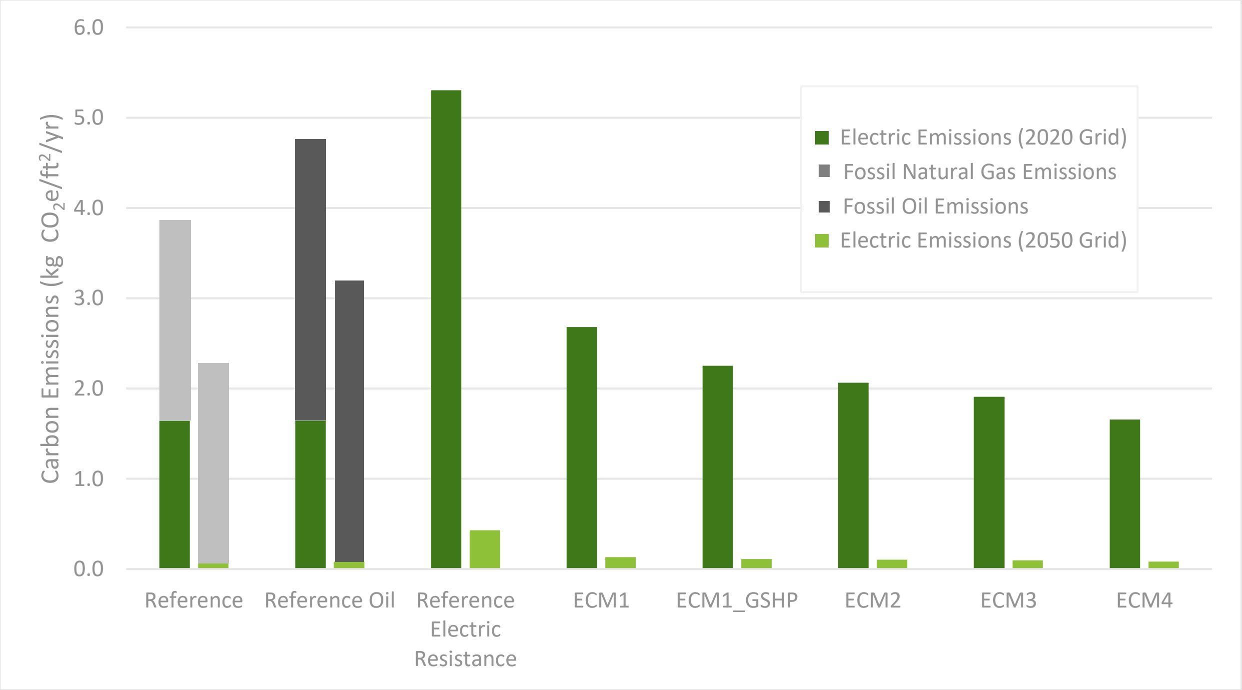
Figure 16. Site energy use intensity for ECM packages applied to Pre-1950 Single Family Residential buildings.



BOX 1: SKATING TO WHERE THE PUCK IS GOING:

Building electrification can be colloquially summarized with a quote from Wayne Gretzky: “Skate to where the puck is going, not where it has been.” The carbon intensity of the grid will decline over the next 30 years with the deployment of renewables. Building electrification leverages this transition by shifting to this energy source that is anticipated to become less carbon intensive at a faster and more cost-effective pace than what is anticipated for liquid or gaseous fuels. Figure 17 illustrates this point by showing the carbon emissions associated with the application of each of the ECM packages for a pre-1950’s single family home in comparison to current emissions form retrofitted homes with natural gas, oil, and electric resistance. Under today’s grid, electric resistance heating is more carbon intensive than heating with fossil fuel sources of heat; a more renewable grid mitigates that. Notably, electric resistance home heating is prevalent in many homes in Quebec, due to the availability of low-cost hydroelectricity, which also results in that region’s electricity supplies having a very low carbon intensity. The application of heat pumps and varying degrees of energy efficiency lower overall emissions, both today and in 2050. Efficiency packages have smaller emissions savings benefits, assuming the application of annual aggregate carbon intensity factors. The application of heat pumps both reduces emissions now and more so over the long term as the grid decarbonizes.

Figure 17. CO_2e emissions intensities for each ECM applied to Pre-1950s Single Family Residential buildings. Aggregate annual emissions factors are used to calculate emissions. 2050 Grid emissions factor is from the All Options pathway analyzed in the Energy Pathways Report.



5.2.1.3 ECM Impacts: Instantaneous Demand

While the aggregate energy and emissions savings associated with the increasingly aggressive building envelope and system improvements provide energy consumption savings, additional benefits may be achieved by reducing the peak or overall instantaneous (e.g., hourly) load of the building. As noted above, electrification will substantially increase both the total aggregate electricity consumption as well as the amount demanded at certain times (instantaneous loads). Heating electrification will shift and increase building peak electrical loads from the summer – currently driven by cooling – to winter for heating. This increase in electricity demand both for aggregate consumption and peak load has three levels of impact relevant to building-energy systems:

- **Building level:** increased electrical loads may increase the level of electrical service required by a building. This may require upgrading the electric panel or switchgear and connection lines. Lowering thermal demand within a building will lower the capacity of the heating unit, lowering equipment costs, and subsequently lower the electrical load demanded by the unit.
- **Distribution level:** increased aggregate electrical local (neighborhood-to-municipal scale) loads requires upgrading substations, feeders, and distribution lines by utility providers. This increases electricity distribution service costs for building owners and those paying electricity bills.
- **Generation level:** increased aggregate regional (e.g., state-to-Northeast scale) loads will require additional electricity generation resources to meet demand. This increases overall energy supply needs as discussed above (Section 2.1) and in the *Energy Pathways Report*. With heating electrification, peak building thermal loads coincide with winter wind generation. Subsequently, wind and supporting resources just need to be appropriately sized to meet this demand. As such, concerns about the peak become less important with respect to emissions. At the generation level, managing peak loads becomes less important as generation becomes dominated by variable renewable resources that can be deployed to levels to meet peak demand. Here, balancing with expensive "peakers" becomes more necessary to meet low supply hours.

These systems thus need to be *sized* at each level to meet the needs of building electrification: heating systems and electrical panels need to be sized to meet sensible heat needs; distribution needs to be sized to meet the delivery needs of the instantaneous peak; and there must be sufficient renewable generation capacity to meet peak demands. Simultaneously, vehicle electrification will also lead to increased investment needs at all these levels. Further, the deployment of distributed energy resources (i.e. solar, storage, flexible vehicle charging) can also impact – mostly lowering – the level of investment needed with respect to managing aggregate demand and instantaneous load. Despite this, investment at these levels will increase with energy demands. Investment at the building level in efficiency and flexible resources can counteract this by limiting aggregate, and more importantly instantaneous peak demand.

Here, we explore the impact of end-use efficiency on the load, as delivered by ECM packages 2-4. This is illustrated in Figure 18 and Figure 19. Figure 18 shows the thermal load and peak electrical demand relative to the reference case. With electrification only and no building envelope improvements, peak loads increase by 73%. Notably ECM1 exhibits an 11% increase in thermal load in part due to the application of automated setpoints for increased comfort. Such action could reflect a rebound effect in the buildings sector associated with better system or an increased desire for comfort when a building is retrofitted. ECM packages 2 and 4 which incrementally add building envelope improvements respectively provide a 23% and 42% reduction in peak load demand relative to ECM 1. This exceeds the average reduction in aggregate demand, 18% and 38%

respectively. For comparative purposes ECM 2 is shown with an ASHP, electric resistance, and gas sensitivities. Load increases dramatically under electric resistance but declines dramatically if ECM 2 is applied without electrification. This is due to lower cooling needs after improving building envelopes. Ground source heat pumps (GSHP) are also effective at lowering peak demand by 23%, while only limiting aggregate building electricity consumption by about 14%

Figure 18. Annual space conditioning EUI, electricity EUI and peak electricity demand.

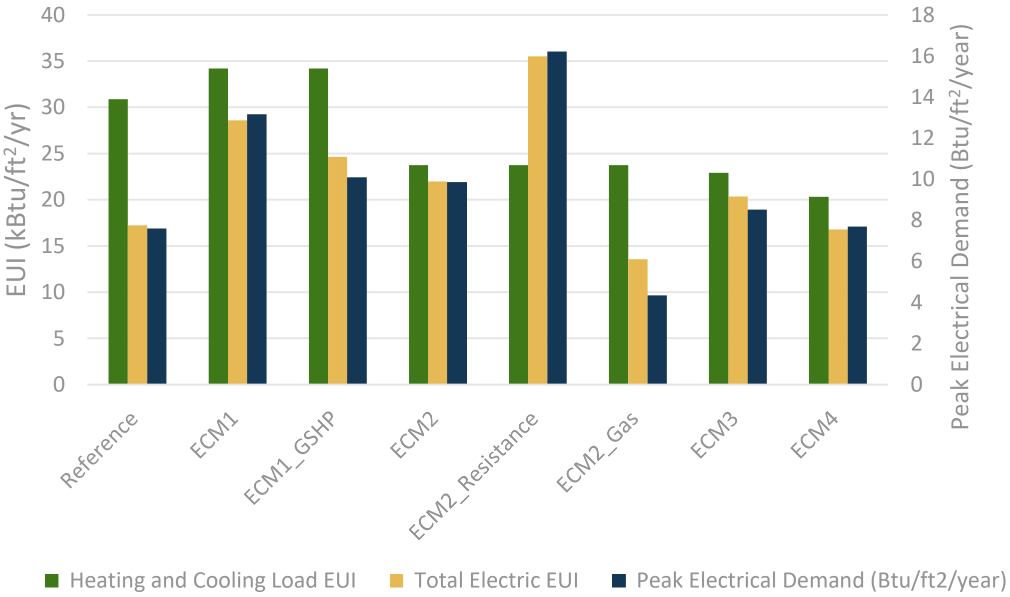
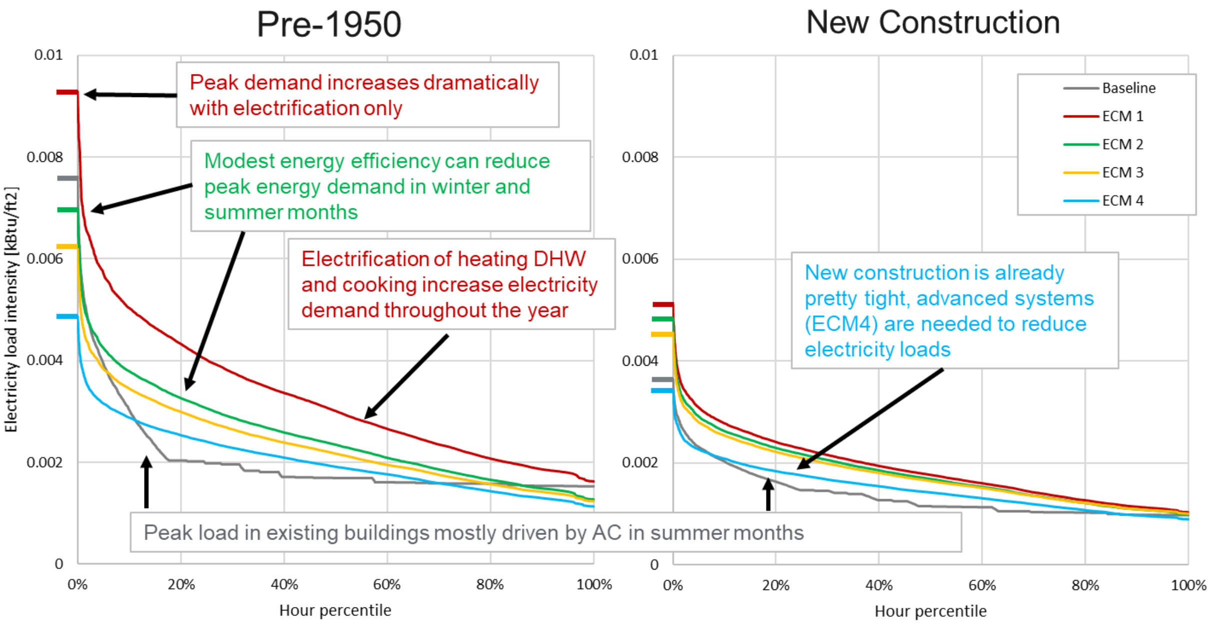


Figure 19 provides an additional perspective on the application of the ECM's on instantaneous building load. Here a pre-1950's building is compared to a new construction single family. Electrification substantially increases electricity demand in all hours of the year in the pre-1950's vintages. Modest energy efficiency provides reductions throughout the year and more so at peak hours. ECM packages 2-4 lower electricity demand below the levels associated with the gas-heated reference building for the most demanding hours of the year – although these peak hours for the reference building are likely summer hours, while the peak hours for the ECM-applied buildings are winter and mix of winter and summer in the shoulder hours (10-40th percentiles of highest load hours). Subsequently, it is important to note that shoulders are still higher in the ECM's compared to the reference. Comparatively, new construction already provides a highly insulated building envelope with low air infiltration. As such, advanced systems improvements (ECM4) are ultimately necessary to reduce electricity demand significantly relatively to an electrified, but code-compliant new building (ECM1).

Figure 19. Building electricity load duration profile for selected Single-Family Home vintages. Hours for each modeled level of intervention are sorted from highest to lowest. Each building ECM is ordered independently in this figure meaning that calendar (equivalent weather) days are not aligned. For example, the baseline peak hours are in the summer while the peak hours for the retrofitted buildings are predominantly in the winter.


Peak demand increases dramatically with electrification only

Modest energy efficiency can reduce peak energy demand in winter and summer months

Electrification of heating DHW and cooking increase electricity demand throughout the year

New construction is already pretty tight, advanced systems (ECM4) are needed to reduce electricity loads

Peak load in existing buildings mostly driven by AC in summer months

5.2.1.4 Cost of Electrification and Efficiency.

The economics of electrifying buildings – particularly small residential homes – has been covered exhaustively elsewhere[50,51,52,53] and has largely shown that replacing oil, propane and electric resistance heating with air source heat pumps in small residential buildings is economically advantageous for homeowners and residents. Depending on assumptions regarding the price of natural gas, electricity, discount rates, and heat pump performance, the costs associated with natural gas to ASHP conversions range from modestly higher to modestly lower. The reader is encouraged to review the cited studies to better understand the influence of such sensitivities, particularly reference 50.

A common assumption that underlies the economic advantages of building electrification is the assumption that conversions occur at the end of life of fossil fuel-based equipment assets that are fully depreciated. This allows for direct comparison of the cost of new heat pumps with new fossil fuel systems rather than comparing the cost of a new heat pump system with a partially depreciated fossil fuel system. Building energy system lifespans range from 10-15 years for water heaters, to 15-30 years for HVAC systems, and to over 40 years for

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[50] Rocky Mountain Energy. *The Economics of Electrifying Buildings*. 2019. https://rmi.org/wp-content/uploads/2018/06/RMI_Economics_of_Electrifying_Buildings_2018.pdf

[51] Rhode Island Division of Public Utilities and Carriers. *Heating Sector Transformation in Rhode Island.* 2018. http://www.energy.ri.gov/documents/HST/RI%20HST%20Final%20Pathways%20Report%204-22-20.pdf

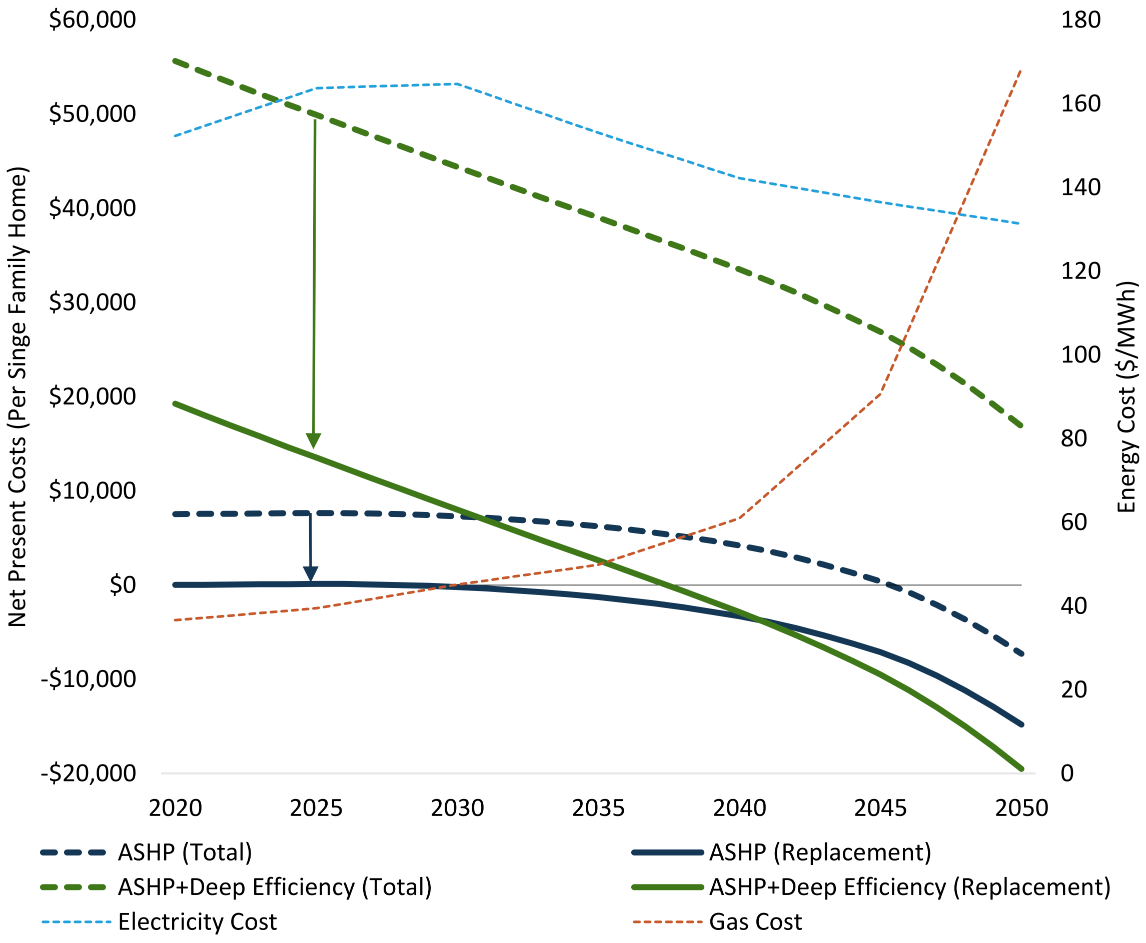
[52] NEEP. *Northeast/Mid-Atlantic Air-Source Heat Pump Market Strategies Report 2016 Update.* 2017. https://neep.org/sites/default/files/NEEP_ASHP_2016MTStrategy_Report_FINAL.pdf

[53] Synapse Energy Economics Inc. *Switch on the Savings: A Heat Pump Cost-Effectiveness Study.* 2018. https://www.synapse-energy.com/about-us/blog/switch-savings-heat-pump-cost-effectiveness-study

building envelopes. Since Massachusetts has committed to net-zero emissions in 30 years, electrification of heating equipment and improvement of building envelopes at end of life transition points is essential to avoid stranded assets and the costs of premature conversions.

Figure 20 shows net present costs of electrification and efficiency measures (ECM1 and ECM4) to illustrate these dynamics using a total cost (dashed lines) and an assumed incremental or replacement cost (solid lines) relative to a gas and air conditioning reference case. The analysis uses delivered gas and electricity cost data from the *Energy Pathways Report's* central benchmark decarbonization case to show how costs will be paid back following a capital investment in electrification and efficiency in 2020. The increase in gas costs in the 2040's is due to higher delivery costs to maintain the distribution systems while connections decline. The total cost example would represent replacing a brand-new furnace. This is an extreme example that is used here to bookend the range of potential costs to illustrate the value of interventions conducted at the end of life.

Figure 20. Payback forecast for the application of ECM1 (electrification) and ECM4 (electrification and deep retrofits) for a Pre-1950 Single Family Home. Dashed lines represent total costs, while color-corresponding solid lines represent incremental replacement costs assuming end of life for gas furnace and air conditioning and in the case of ECM4 a 60% reduction in costs – assuming actions were taken as part of a necessary renovation. Underlying energy price forecasts (right axis) are shown in the dotted lines and are derived from the All Options pathway from the Energy Pathways Report. Break-even is represented by a thin line at $0. Future energy expenditures are discounted at 3%. Future replacements are assumed to happen at zero cost.



The installation cost of an ASHP system in this example is about $7,500 and from a total cost basis. It would not be paid back until 2045 (dashed blue line) when gas prices increase. When installed at the end of life, there is very little difference in installation costs between an ASHP and a gas furnace (solid blue line) and in the near term also little difference in operating costs. Deep efficiency actions typically can exceed $50,000 per home, as shown with this example (dashed green line). Here, identifying an end-of-life point is more challenging due to the longer lifetimes of building envelopes, but could be associated with a major retrofit. In such cases new insulation and systems would be installed anyways, and the $20,000 cost modeled here assumes the installation of higher-performing versions of these (solid green line).

Implementing ECM 4 at an end-of-life event would thus be essential for ensuring a reasonable, albeit 17-year, payback. The lower electricity demand associated with ECM 4 also results in a faster rate of payback represented by the relatively steeper slope. This analysis does not factor in costs savings associated with reduced equipment size or distribution system infrastructure, which would further push down the curve (solid green line).

Gas largely becomes more expensive because declining consumption requires higher rates on delivery to recoup the costs of pipeline maintenance. It is important to emphasize the fact that cost savings in later years are largely driven by avoiding use of increasingly expensive delivered gas. Further, if intentionally substituted, the use of zero-carbon gas would nearly double the costs modeled here, based on assumptions in the *Energy Pathways Report*.

Timing electrification and efficiency measures with end-of-life transition points is essential to minimize costs. Since heating equipment and envelops have 20-30+ year lifespans, immediately electrifying and strategically pursuing efficiency measures is essential for cost-effective mitigation.

BUILDING HEAT STRESS

Approximately 20% of Massachusetts households do not have any home air conditioning, and another almost 60% rely on a window or wall AC unit. National data indicate that lower-income populations have less access to air conditioning than higher-income populations (2009 Residential Energy Consumption Survey). Even in today's climate, indoor temperatures can rise to unsafe levels, putting occupants at a potential health and safety risk.

Using models of a Pre-1950-era Single Family Residence (SFR) and a New Construction-style SFR, it was calculated that indoor dry-bulb temperatures may exceed 91°F— the temperature above which heat exhaustion and heat stroke become a risk according to the Mayo Clinic—14% and 17% of the year, respectively. The latter is due to improved airtightness and thermal insulation trapping heat inside of the building with no air conditioning system to remove the heat.

This issue is exacerbated by a warming climate. Using the RCP 8.5 95th percentile weather data for 2050 which has a simulated week-long heat wave, modeling for both the Pre-1950 case as well as the New Construction case showed a nearly 40% increase in the number of hours spent with the indoor temperature above the dangerous 91°F threshold, resulting in the Pre-1950 case and the New Construction case exceeding safe thresholds 19% and 23% of the year, respectively (Table 14).

Considering that demand for air conditioning will grow as the climate warms, heat pumps are a natural fit to both handle increased cooling demands and electrify heating demands with a single system.

Table 14. Distribution of hours within each temperature bin for the following scenarios: (1) 2016 weather with and without air conditioning, and (2) 2050 weather with air conditioning sized for today's weather and 2050 weather without air conditioning.

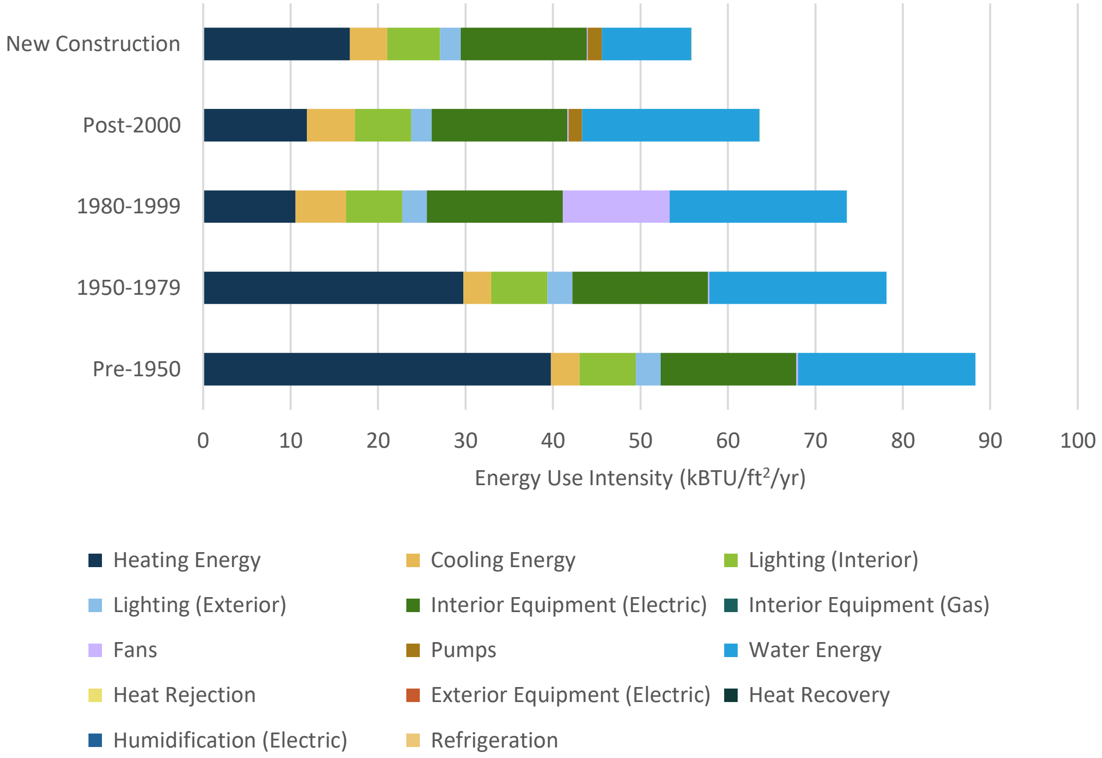
Temp. Bin [F]	**New Construction SFR**				**Pre-1950 SFR**			
	2016 Weather		**2050 Weather**		**2016 Weather**		**2050 Weather**	
	Baseline	**No A/C**	**Baseline A/C with Future Weather**	**No A/C with Future Weather**	**Baseline**	**No A/C**	**Baseline A/C with Future Weather**	**No A/C with Future Weather**
55-59	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
60-64	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
65-69	12.8%	12.8%	11.5%	11.5%	0.0%	0.0%	0.0%	0.0%
70-74	41.7%	40.9%	38.2%	37.8%	58.7%	58.6%	53.9%	53.8%
75-79	28.9%	10.1%	31.8%	9.3%	10.2%	9.8%	9.6%	9.3%
80-84	16.6%	9.5%	18.5%	8.7%	11.0%	9.4%	11.4%	9.7%
85-89	0.0%	10.1%	0.0%	9.9%	20.1%	8.3%	25.2%	8.1%
90-94	0.0%	**8.6%**	0.0%	**9.9%**	0.0%	**5.9%**	0.0%	**7.7%**
95-99	0.0%	**5.5%**	0.0%	**7.4%**	0.0%	**4.2%**	0.0%	**5.5%**
100-104	0.0%	**2.2%**	0.0%	**3.8%**	0.0%	**2.4%**	0.0%	**3.4%**
105-109	0.0%	**0.5%**	0.0%	**1.2%**	0.0%	**1.1%**	0.0%	**1.8%**
110-114	0.0%	0.0%	0.0%	**0.4%**	0.0%	**0.3%**	0.0%	**0.5%**
115-119	0.0%	0.0%	0.0%	**0.1%**	0.0%	0.0%	0.0%	**0.2%**
120-124	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.03%**
Exceeds Safe Threshold	0.0%	**16.7%**	0.0%	**22.8%**	0.0%	**13.8%**	0.0%	**19.2%**

5.2.2 **Large Multifamily Residential**

5.2.2.1 Building Stock Summary

Large multifamily buildings (defined as 5+ family residential) are typically characterized as having been built within the last 40 years. While energy use in the large multifamily typologies is still characterized by large space and water heating demands, domestic hot water use is a larger energy driver than in smaller residential typologies due to the thermal efficiency of having denser units and less envelope exposure per unit. Furthermore, this building typology is characterized by newer construction, which requires less heating energy in most cases from having tighter building envelope (Figure 21).

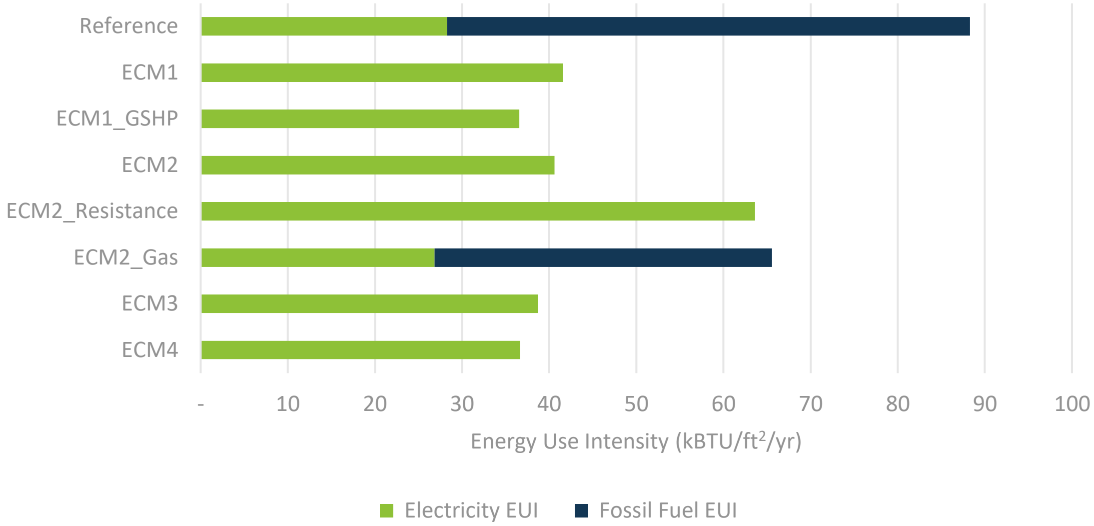
Figure 21. Energy use intensity for reference Large Multifamily (20+ Units) Wood vintages.



5.2.2.2 ECM Impacts

While this building class can be expeditiously electrified by installing unit HPWHs and ductless mini-splits or with more integrated strategies, opportunities for deep efficiency gains are likely more limited. Figure 22 shows limited potential in reducing aggregate electricity demand after electrification. End-use efficiency savings associated with ECM's 2-4 range from 2%-12% aggregate and 6-18% for peak demand.

Figure 22. Site energy use intensity for ECM packages applied to Pre-1980 Large Multifamily (20+ Units) Wood buildings.

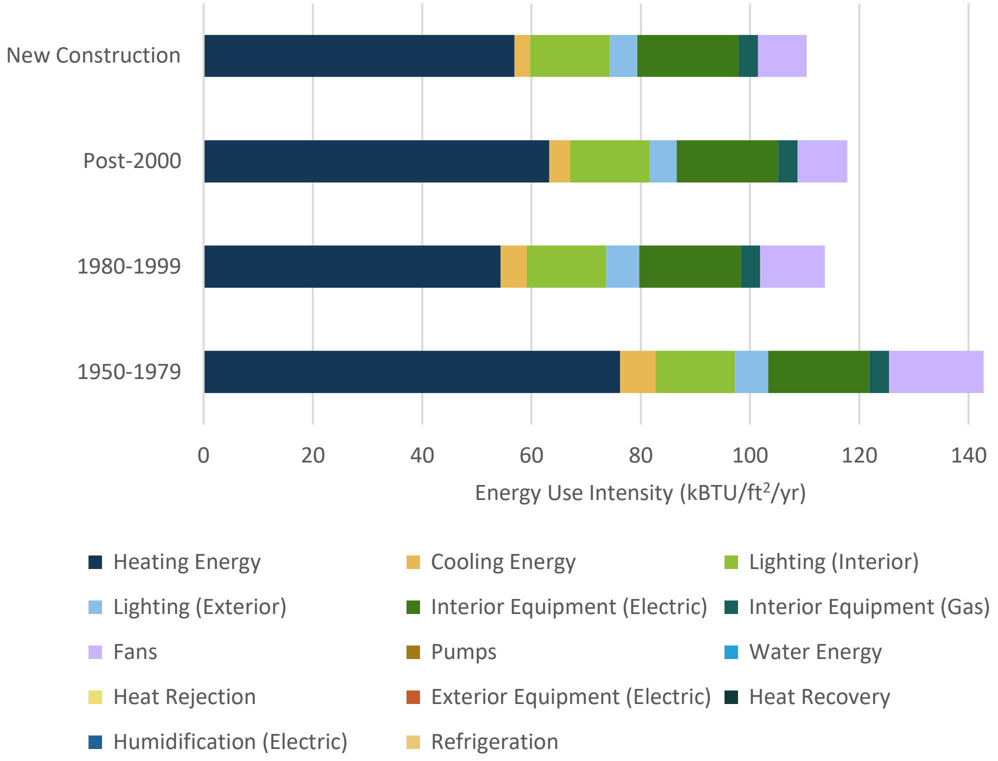


5.2.3 Small and Simple

5.2.3.1 Building Stock Summary

The small and simple category comprises small offices (under 5,000 square feet), medium offices (5,000-50,000 square feet), retail, and supermarkets. These typologies are most often characterized as using off-the-shelf standalone HVAC systems and typically do not utilize complex control systems or operating strategies. This portion of the building stock represents 7% of all built square footage in Massachusetts. Energy use in the small and simple typologies are characterized by large space heating demands, particularly in older vintages (Figure 23). Given more than half of the small and simple buildings in the Commonwealth are over 40 years old, addressing space heating is crucial in decarbonizing these typologies.

Figure 23. Energy use intensity for reference Retail vintages.



5.2.3.2 ECM Impacts

Simultaneously electrifying and adding demand control ventilation and energy recovery systems substantially improves the performance of small commercial buildings (Figure 24). Application of aggressive envelope and advanced systems measures (ECM4) yields only an increase 12% reduction in aggerate electricity demand and a 22% reduction in peak loads relative to ECM 1 for a pre-1980s vintage (Figure 25) and less with newer vintages.

Figure 24. Site energy use intensity for ECM packages applied to Pre-1980 Retail buildings.

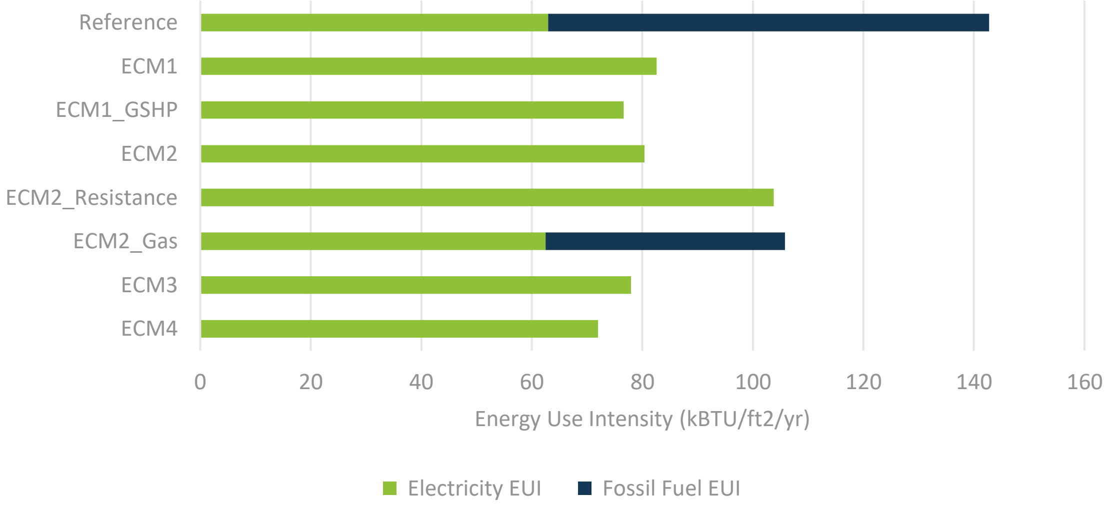
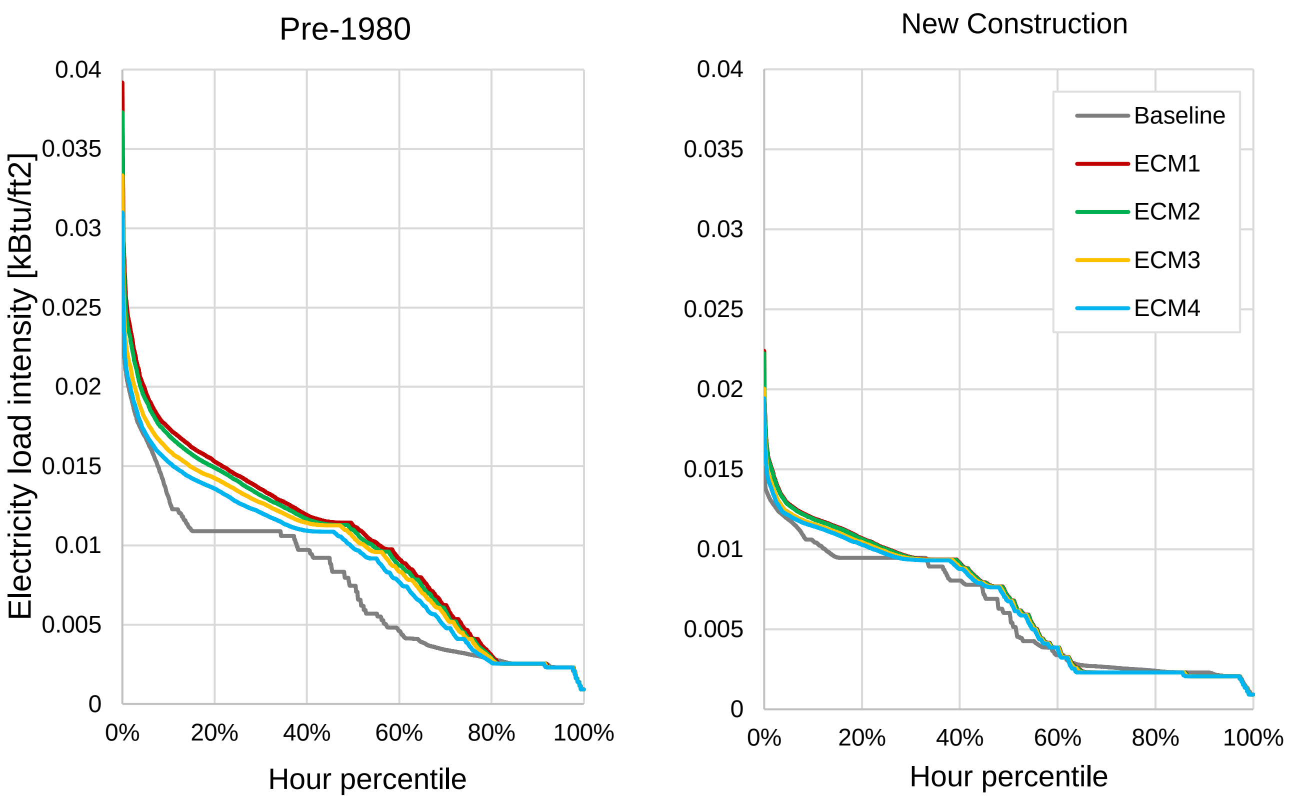


Figure 25. Building electricity load duration profile for selected retail vintages. Hours for each modeled level of intervention are sorted from highest to lowest. Each building ECM is ordered independently in this figure meaning that calendar (equivalent weather) days are not aligned. For example, the baseline peak hours are in the summer while the peak hours for the retrofitted buildings are predominantly in the winter.



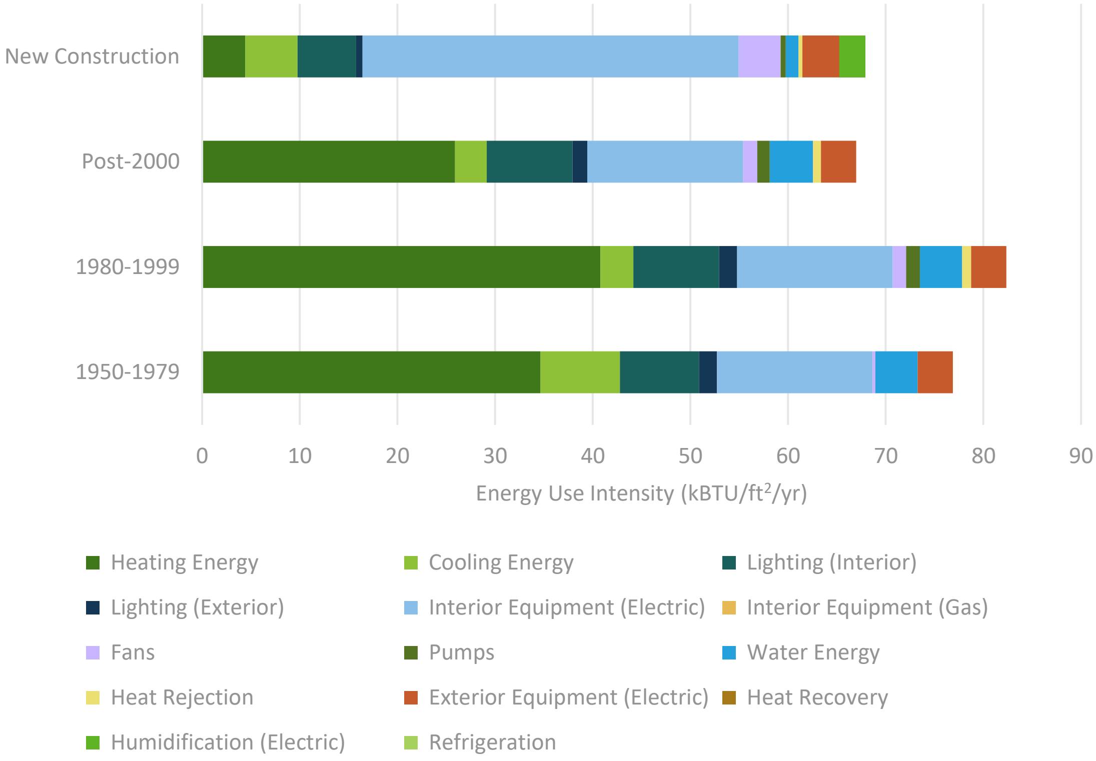
5.2.4 **Large and Complex**

5.2.4.1 Building Stock Summary

The large and complex category comprises large offices and convention/assembly buildings. These typologies are most often characterized as using professionally designed, whole-building HVAC systems with large scale equipment with integrated controls. This portion of the building stock represents 9% of all built square footage in Massachusetts, large office alone is 8%.

Energy use in the large and complex typologies are characterized by large internal heat gains, high heating demand due to ventilation loads for air-based systems to provide space heating and cooling and building envelope loads. Given the majority of the large and complex typologies in the Commonwealth are characterized by inefficient fossil fuel heating systems and leaky, thermally-transmissive envelopes, optimizing heating demands and retrofitting heating equipment is key in decarbonizing these typologies. The most effective strategies in this typology are decoupling ventilation from thermal demands and air-side energy recovery. It should be noted that the DOE prototype model for new construction includes higher plug loads and a data center to reflect the prevalence of increased IT loads in newer office buildings. Based on design experience, this feature was retained to incorporate IT load demands in urban areas. It should be noted that this increased internal load decreases heating demands and increases cooling demands. Figure 26 shows the energy use intensity for reference type Large Office vintages.

Figure 26. Energy use intensity for reference Large Office vintages.



5.2.4.2 ECM Impacts

The unique features of large buildings, such as significant internal gains and under-performing HVAC systems, make them suitable for heating electrification. Electrification of heating via VRF heat pumps, coupled with systems upgrades (ECM1) help optimize building energy use with modest impacts to electricity demands (Figure 27 and Figure 28). Application of ECM1 to a 1950-1979 vintage large office building increases aggregate electricity demand by only 4.6% (Figure 27) and can reduce peak loads. This is in part due to ECM1 for large building including demand-control ventilation and energy recovery systems which help to balance and optimize thermal loads across the building. While heating demands are electrified, these are relatively small compared to other building classes due to the large internal gains. Improved HVAC systems reduce cooling needs. The application of envelope and windows measures (ECM packages 2-4) only reduces electricity demands by 11%, but reduces peak demands in the top 10% of hours each year by 20%-40%.[54] The potential application of HPWHs delivers some additional modest savings. These results show that electrification can be achieved with little overall changes to electricity demand in large office buildings.

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[54] In the modeled 1950-1980 modeled vintage, two sequential early morning hours in the middle of February exhibited drastically higher loads than others. Presumably such spikes can be avoided through setpoint fallbacks or building-level demand response.

Figure 27. Site energy use intensity for ECM packages applied to 1950-1980 Large Office buildings.

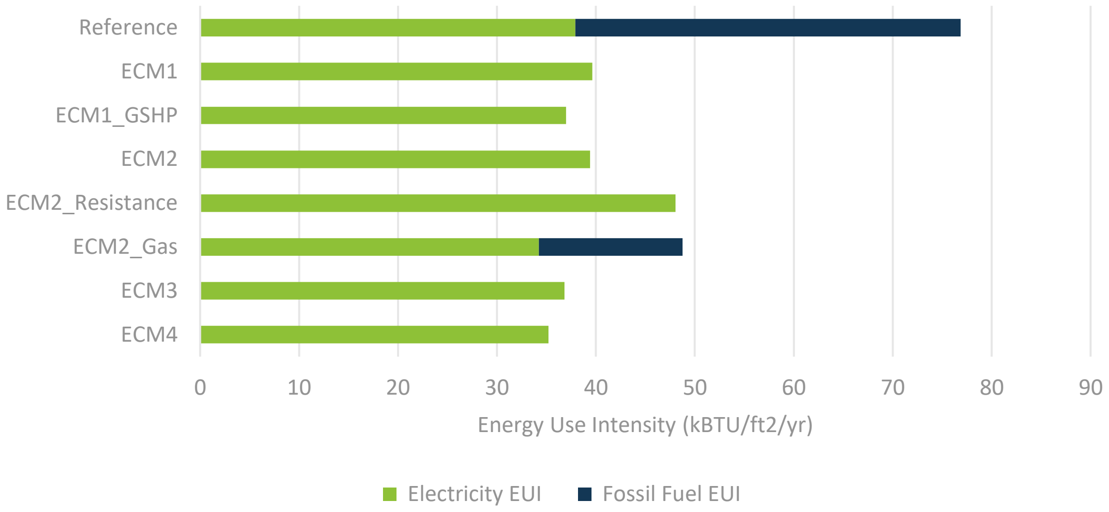
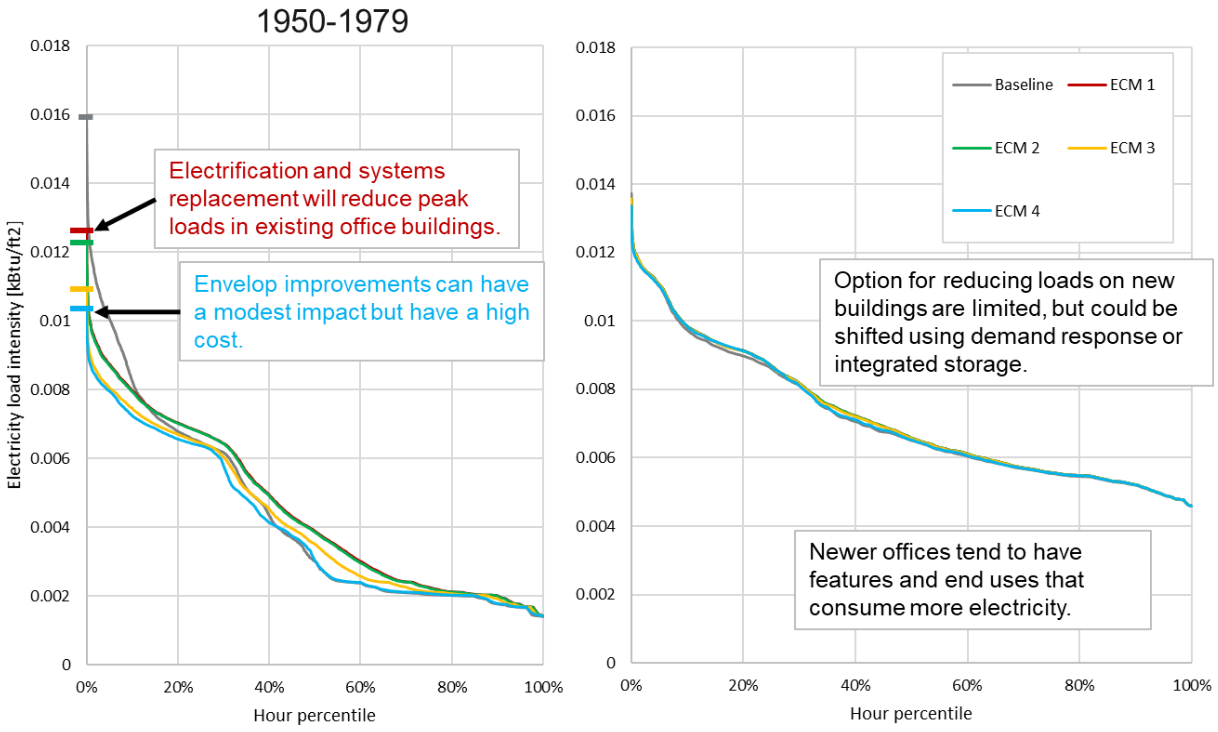


Figure 28. Building electricity load duration profile for selected Large Office vintages. Hours for each modeled level of intervention are sorted from highest to lowest. Each building ECM is ordered independently in this figure meaning that calendar (equivalent weather) days are not aligned. For example, the baseline peak hours are in the summer while the peak hours for the retrofitted buildings are predominantly in the winter.



Electrification and systems replacement will reduce peak loads in existing office buildings.

Envelop improvements can have a modest impact but have a high cost.

Option for reducing loads on new buildings are limited, but could be shifted using demand response or integrated storage.

Newer offices tend to have features and end uses that consume more electricity.

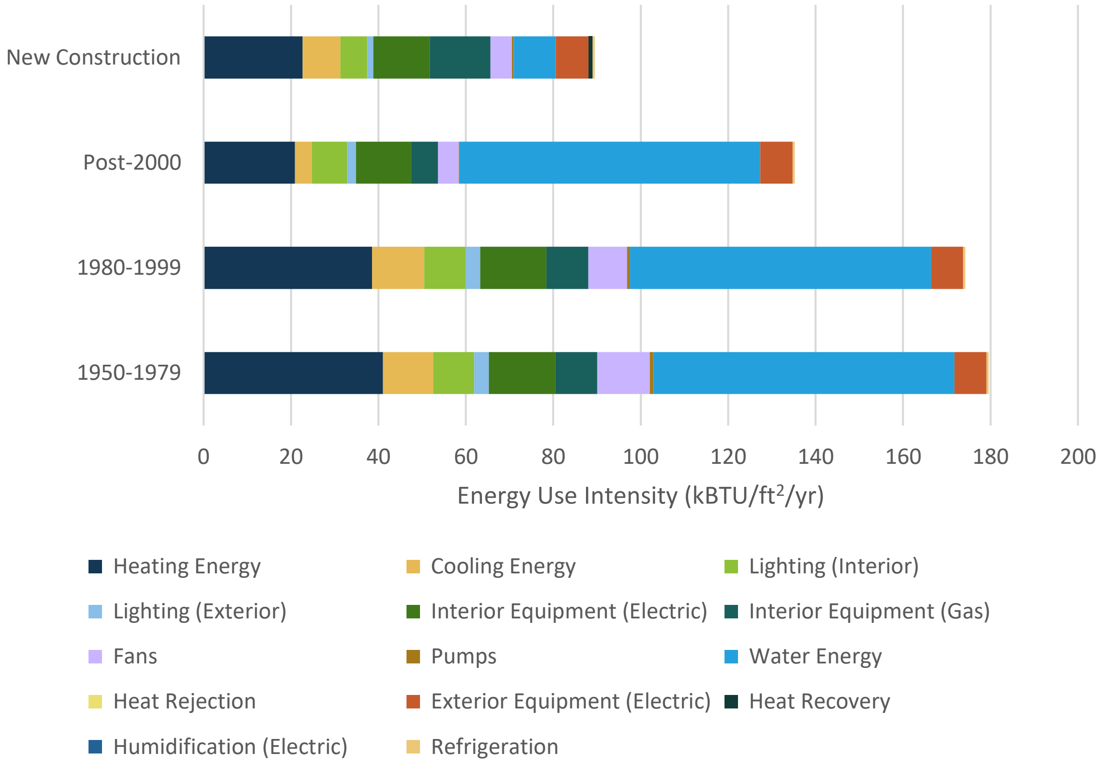
5.2.5 **DHW-Driven**

5.2.5.1 Building Stock Summary

The DHW-driven category comprises hotels and restaurants. These typologies often use off-the-shelf HVAC systems and do not typically utilize complex control systems or operating strategies. DHW represents a larger percentage of their overall energy use than other typologies. This portion of the building stock represents just over 1% of all built square footage in Massachusetts.

Figure 29 illustrates how energy use in the DHW-driven typologies is eponymously characterized by large water heating demands. While space heating is a secondary driver and will benefit from being addressed as well, retrofitting inefficient fossil fuel-based water heating systems with heat pump-based or solar water heating systems is critical in decarbonizing these typologies.

Figure 29. Energy use intensity for reference Hotel vintages.



5.2.5.2 ECM Impacts

Like the large office buildings described in the previous section, DHW-driven hotels and restaurants each undergo heating and hot water electrification with the addition of demand-control ventilation and energy recovery. This allows these spaces to more optimally utilize energy flows. For example, heat pump water heaters simultaneously generate cooling capacity with hot water. This cooling capacity can be used to further cool kitchen spaces, that are simultaneously modeled to have reduced cooling demands by converting from gas to electric cooking. Energy efficiency actions (ECM packages 1-4) provide a only a modest reduction to aggregate and peak loads (Figure 30, Figure 31) due to the high process loads of these buildings.

Figure 30. Site energy use intensity for ECM packages applied to 1950-1979 restaurant buildings.

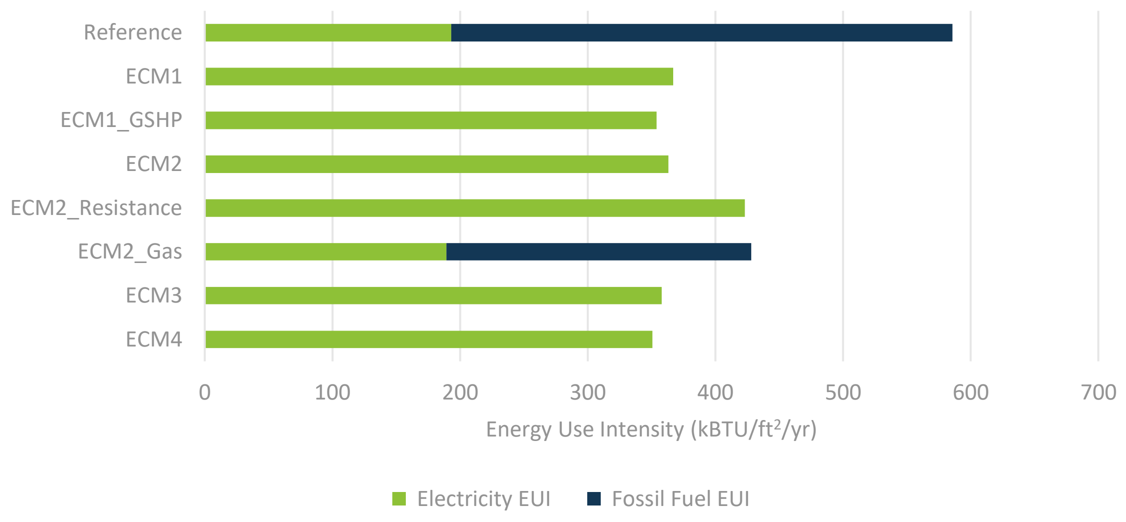
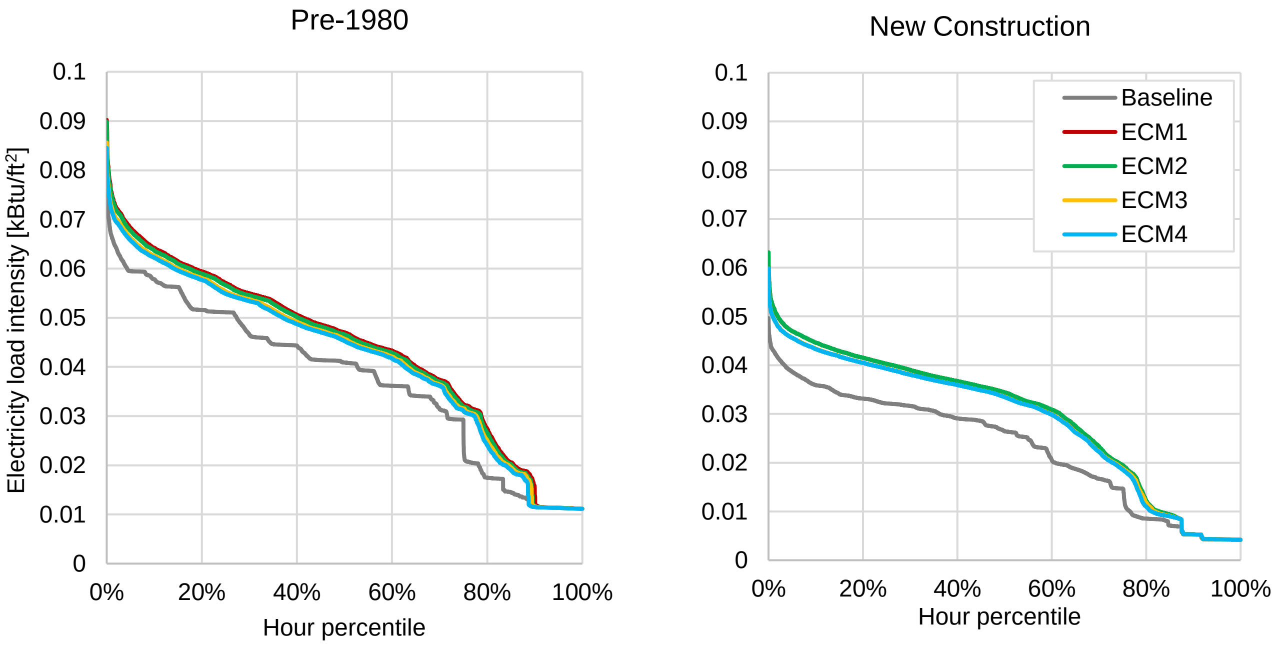


Figure 31. Building electricity load duration profile for selected restaurant vintages. Hours for each modeled level of intervention are sorted from highest to lowest. Each building ECM is ordered independently in this figure meaning that calendar (equivalent weather) days are not aligned. For example, the baseline peak hours are in the summer while the peak hours for the retrofitted buildings are predominantly in the winter.

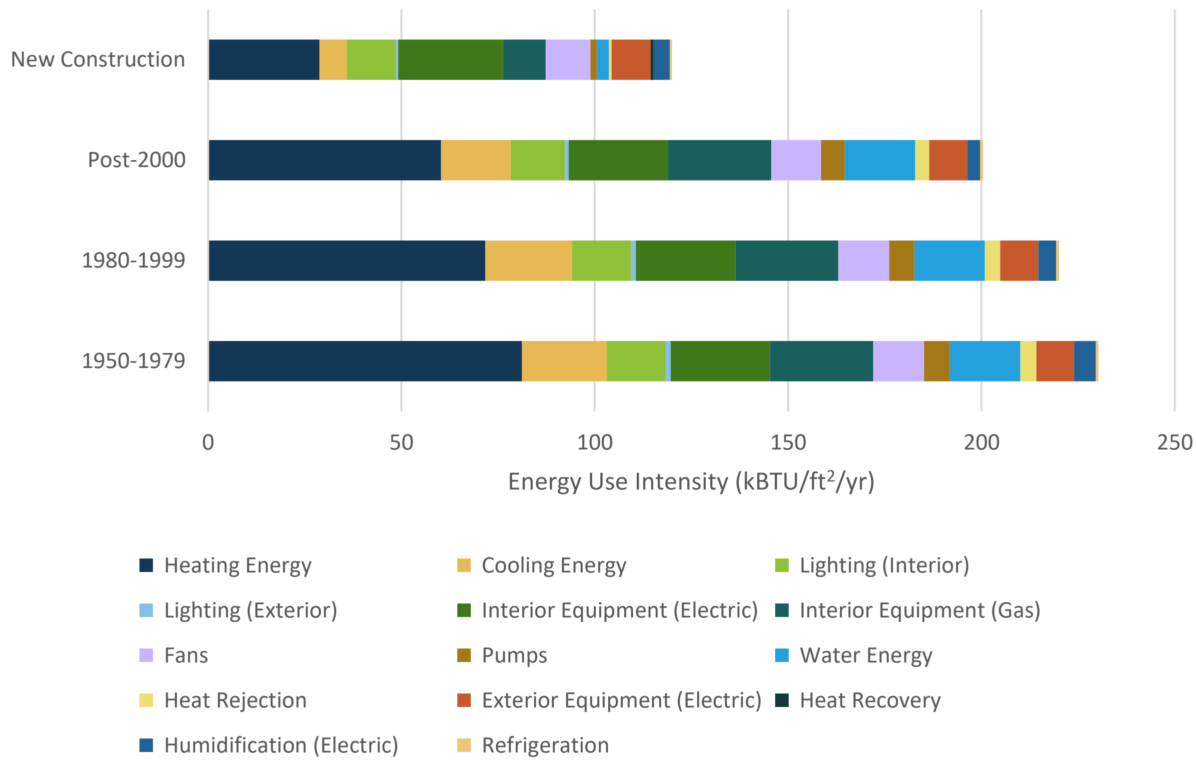


5.2.6 **Ventilation-Driven**

5.2.6.1 Building Stock Summary

The ventilation-driven category comprises hospitals and laboratories. These typologies are most often characterized as having professionally designed HVAC systems with high ventilation and room airflows that are driven by health, safety, and code requirements. This portion of the building stock represents just over 1% of all built square footage in Massachusetts. Energy use in the ventilation-driven typologies are characterized by large airflow and outside air requirements. These large airflows serve various functions ranging from exhausting laboratory fume hoods to pressurizing operating rooms and hospital patient rooms and for infection control. As such, the amount of air required for these purposes often exceeds the cooling demands within spaces, increasing the demand for reheat. As such, decoupling ventilation from thermal demands where allowed, taking advantage of simultaneous need for heating and cooling, energy recovery, and minimizing fan energy to the extent possible is key in decarbonizing these typologies. The energy use intensity for reference Hospital vintages is show in Figure 32.

Figure 32. Energy use intensity for reference Hospital vintages.



5.2.6.2 ECM Impacts

Electrical loads in ventilation-driven buildings are already very high to support air movement. The addition of demand-control ventilation and energy recovery systems helps to better optimize building thermal loads limited increases in electricity demand from thermal electrification (ECM1, Figure 33) Because loads are already high, driven primarily by ventilation, improving envelopes will have a limited impact of overall aggregate and peak demands (Figure 33, Figure 34). Again, older structures benefit more than newer structures (though, to a lesser extent than other typologies due to being dominated by internal loads and HVAC operational characteristics).

Figure 33. Site energy use intensity for ECM packages applied to 1950-1979 Hospital buildings.

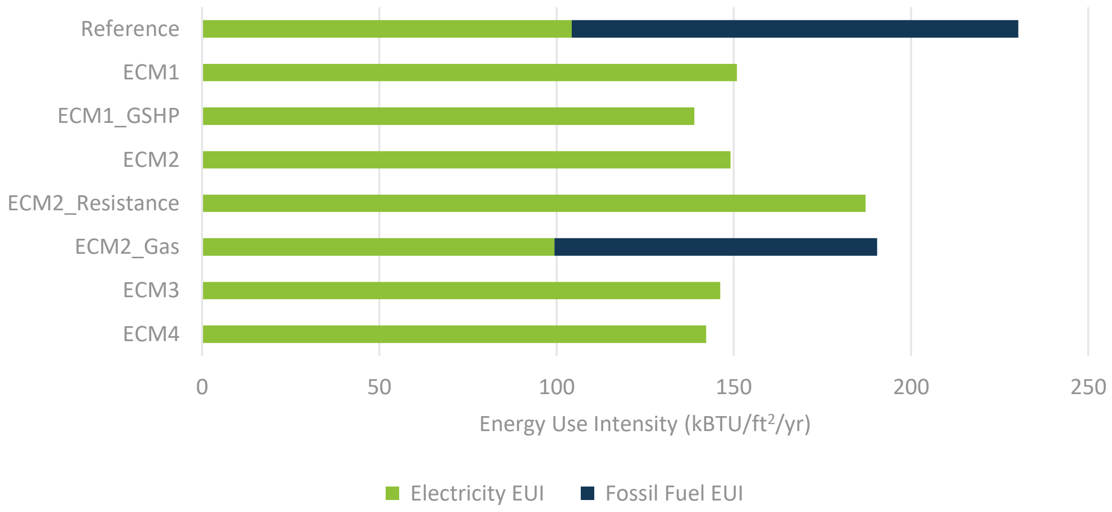
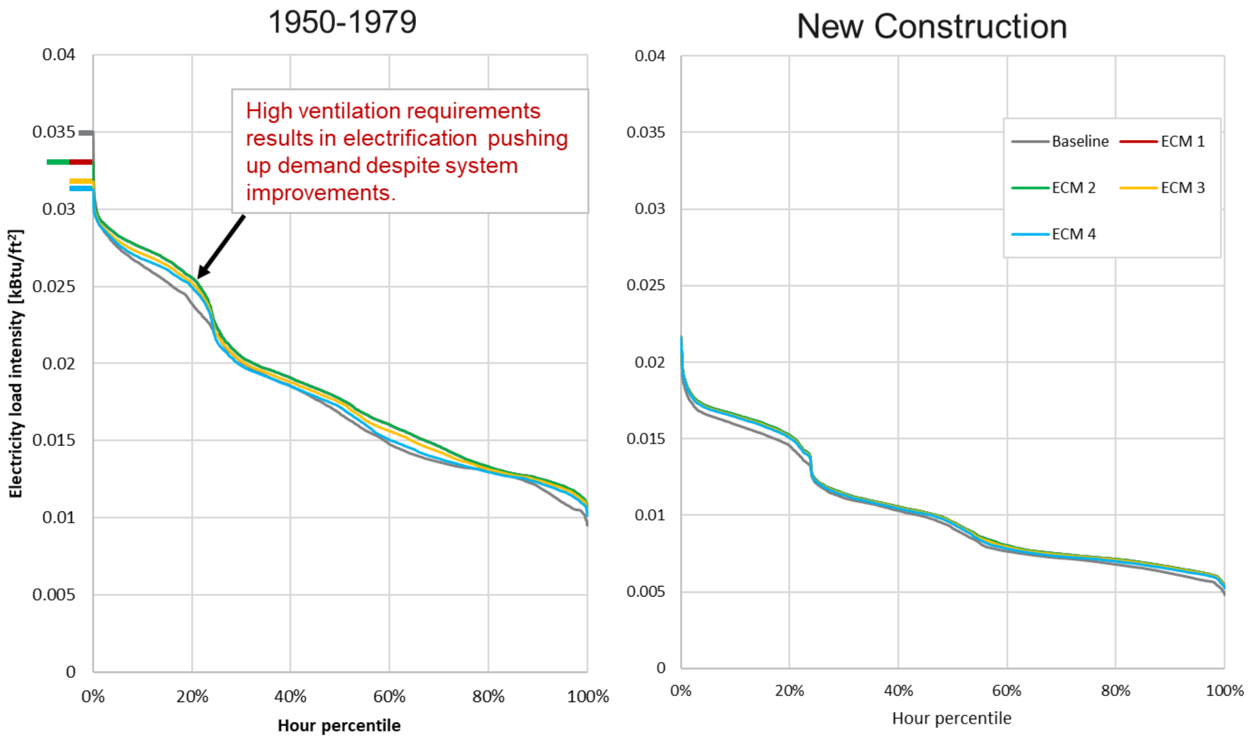


Figure 34. Building electricity load duration profile for selected laboratory vintages. Hours for each modeled level of intervention are sorted from highest to lowest. Each building ECM is ordered independently in this figure meaning that calendar (equivalent weather) days are not aligned. For example, the baseline peak hours are in the summer while the peak hours for the retrofitted buildings are predominantly in the winter.



High ventilation requirements results in electrification pushing up demand despite system improvements.

5.3 Efficacy of Packages in Achieving Emissions and Efficiency Goals

This section uses the building energy model results presented above to identify areas of opportunity and prioritization for decarbonization and efficiency actions across the building stock. The analysis uses total installation costs as opposed to incremental costs. This is done for analytical consistency but may not reflect real world activity; at the end of life of a fully depreciated asset such as a gas furnace, the incremental or differential cost of replacing it with a heat pump relative to a new furnace is much smaller than the total cost of install of either the new heat pump or the new furnace. Conversely, the incremental costs of more complex actions such as deep building retrofits, window replacements, systems interventions are harder to define relative to a consistent reference point. Costs are also likely to be very uncertain for more complex building types, such as large offices, assembly spaces and laboratories. Given these constraints, the cost data presented below should be used to evaluate ECM packages in relation to each other with respect to the building prototypes that they are applied to.

Figure 35 shows a marginal abatement cost curves for building decarbonization via electrification of heating, DHW, cooking, and other process loads (application of ECM1) under various economic assumptions. Table 15 lists the top 20 building types with the greatest mitigation potential, representing 81% of the stock. Figure 38 shows a more detailed representation of the breakdown of the sector's emissions across end uses, buildings and fuel types. Across the sector, over 50% of emissions, result from fossil fuel space heating and over 20% of emissions result from fossil fuel domestic hot water heating.

Most notably, the largest potential for mitigation lies within the single family (6.0 $MMTCO_2$) and small multifamily vintages (3.8 $MMTCO_2$): 37% and 24% of the sector wide technical potential respectively. This is exhibited in the longer segments of Figure 35. The cost effectiveness of decarbonizing the building stock is highly sensitive to the underlying economic assumptions (discount rate, asset life, and incremental costs). Regardless of the economic assumption, the act of electrifying equipment at the end of life is perhaps the most important factor in ensuring the cost effectiveness of decarbonization. While this may seem like an obvious point, it is an important point of emphasis given that there are at most two replacement points for building energy equipment between now and 2050.

Assumption relating to the difference in relative or replacement costs between fossil fuel equipment and electric placement drive some shuffling in cost-ordering of the building typologies: low-energy intensity buildings (offices, retail, schools) becoming relatively advantageous to electrify; more energy intensive buildings (hospitals, laboratories, assembly) become more costly to electrify. It should be noted that costs can be largely uncertain, particularly those associated with more complex and unique commercial buildings. Better identifying what buildings are less amenable to electrification from a feasibility and cost basis is an area of future research.

Figure 36 provides further insight into building decarbonization opportunities. The emissions associated with fuel oil buildings exceed their area share due to the carbon intensity of fuel oil combustion. Switching oil appliances for heat pumps also unlocks significant energy bill savings for building occupants and thus represents a large potential for emissions savings.

Figure 35. Emissions abatement cost curves based upon total or replacement capital costs of building electrification: the application of package ECM1 to existing and new buildings. Left hand side shows an optimistic economic conditions with a low discount rate and long asset lifetime. The righthand side shows a high discount rate and short asset lifetime. Curve does not include commercial emissions gap. Mitigation cost is calculated by spreading costs evenly across a 30-year time horizon.

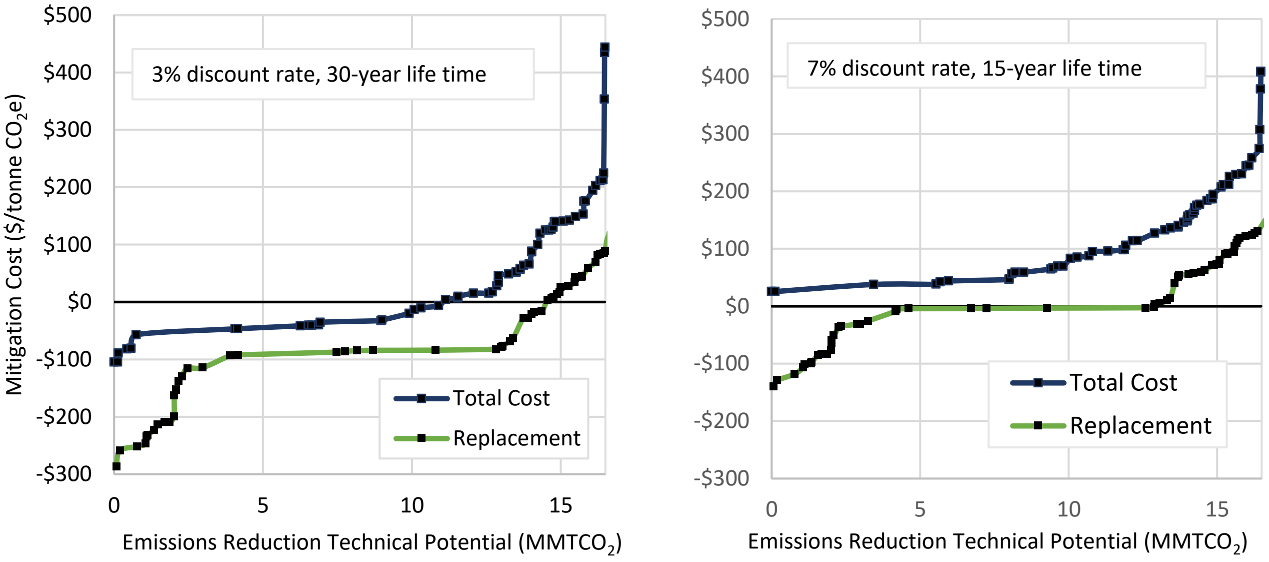


Table 15. Decarbonization potential of top 20 building prototypes with the greatest mitigation potential via electrification.

Typology	Vintage	Emissions Savings Technical Potential		Emissions Savings Cumulative Potential	
		MMTCO$_2$e	%	MMTCO$_2$e	%
Small Multifamily	Pre-1950	3.32	20%	3.32	20%
Single Family	Pre-1950	2.10	13%	5.42	32%
Single Family	1950-1979	2.04	12%	7.45	45%
Single Family	1980-1999	0.92	5%	8.37	50%
Office (Large)	1950-1979	0.59	4%	8.96	54%
Single Family	New Construction	0.52	3%	9.48	57%
Retail	1950-1979	0.52	3%	10.00	60%
Single Family	Post-2000	0.41	2%	10.40	62%
Large Multifamily (5-19 units)	Pre-1950	0.34	2%	10.74	64%
Office (Medium)	1950-1979	0.29	2%	11.03	66%
Small Multifamily	1950-1979	0.28	2%	11.31	68%
Warehouse	1950-1979	0.27	2%	11.58	69%
Large Multifamily (20+ Units) Wood	1950-1979	0.26	2%	11.84	71%
Warehouse	New Construction	0.25	2%	12.09	72%
Large Multifamily (20+ Units) Wood	New Construction	0.25	1%	12.34	74%
Small Multifamily	New Construction	0.24	1%	12.58	75%
Office (Large)	1980-1999	0.23	1%	12.81	77%
Retail	New Construction	0.22	1%	13.03	78%
Large Multifamily (20+ Units) Wood	Post-2000	0.21	1%	13.24	79%
Large Multifamily (20+ Units) Wood	1980-1999	0.20	1%	13.44	80%

Figure 36. Site emissions by typology and end use, grouped in colors by end use.

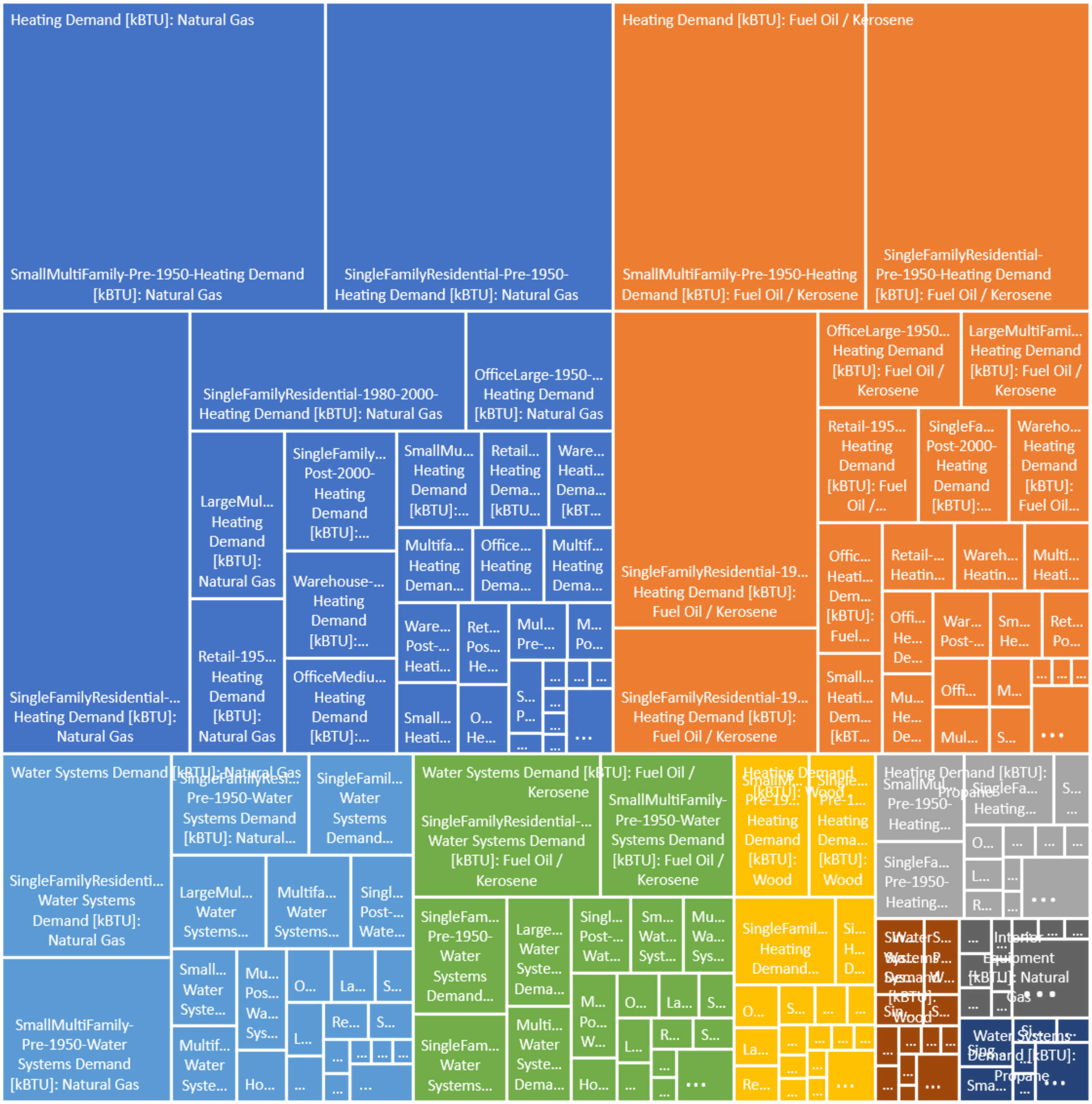


Figure 37 shows energy efficiency cost curves for the application of ECM Packages 2-4 across the entire building stock. Table 16 lists the top 6 building types with the greatest energy reduction potential, representing 81% of the stock, as well as the top 6 building types with respect to each package's cost effectiveness. Figure 38 shows a more detailed representation of energy use across the sector's end uses, buildings and fuel types.

ECM2 represents the application of low-cost envelope interventions: blow-in wall insulation, roof and attic insulation, and air-sealing. ECM2 also includes energy recovery ventilation for the single family and small multifamily building classes.[55] Ventilation is included as part of the package because as building envelopes

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[55] These systems were included as part of ECM1 for all other building classes.

become tighter, infiltration can no longer be relied upon for ventilation. At this level of air tightness, these buildings may require mechanical ventilation for occupant health. ECM2 would have a technical potential of about 4.5 TWh of electricity savings if universally applied to the building stock. The more advanced packages, ECM3 and ECM4, achieve higher technical potentials of 7.7 TWh and 12.8 TWh respectively. From ECM2 to ECM3 to ECM4, energy savings scales with costs resulting in similar levels of costs per kWh across the packages, with the more aggressive packages unlocking more potential. Still, achieving these savings requires significant upfront costs: a $3/kWh/sf/year efficiency package would have a 15-year simple payback at current electricity rates (assuming 20 cents per kWh). Notably, the similar reduction in energy consumed per dollar saved indicates that policies to encourage efficiency should scale to support higher-cost projects. These costs do not include non-building benefits such as reduced distribution capacity needs.

The cost effectiveness of efficiency – measured as the dollars spent per unit of electricity consumption saved – varies across the building stock. Older single family and small multifamily homes offer the greatest technical potential in sector-wide energy savings at some of the lowest costs per unit of energy saved (Table 16). While in general, efficiency measures in larger, complex, and newer buildings are less cost effective, efficiency measures in high ventilation buildings (hospitals and laboratories) tended to be as cost effective as those in the small residential stock. While the technical potential for these buildings is comparatively low, it does emphasize that opportunities for efficiency in the commercial sector exist in specific niches.

Figure 37. Energy abatement cost curve for capital costs of building efficiency measures, the application of packages ECM2, ECM3 and ECM4 to existing and new buildings. Costs and potential are reported relative to ECM1. Analysis uses the All Options electricity prices which do not include taxes and fees. A 3% discounted rate and 30-year lifespan is assumed.

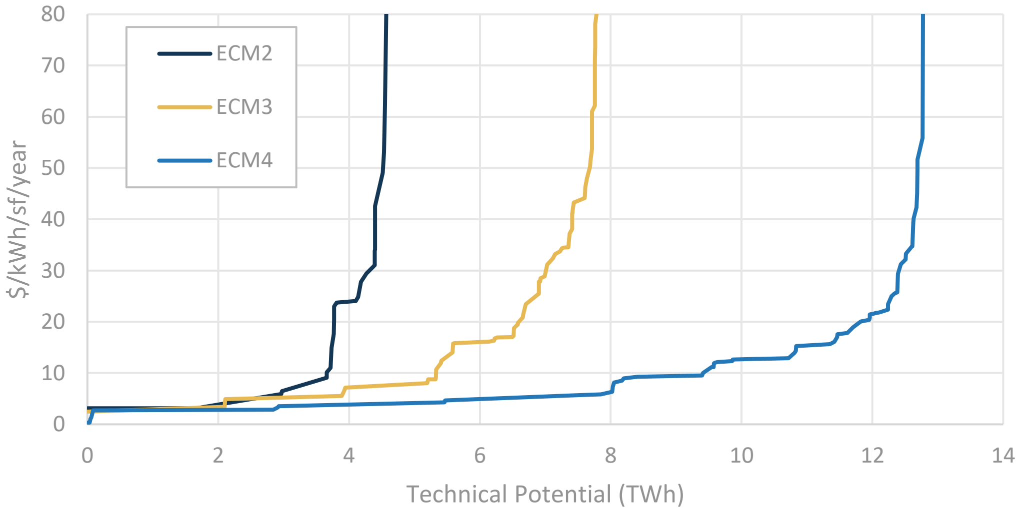
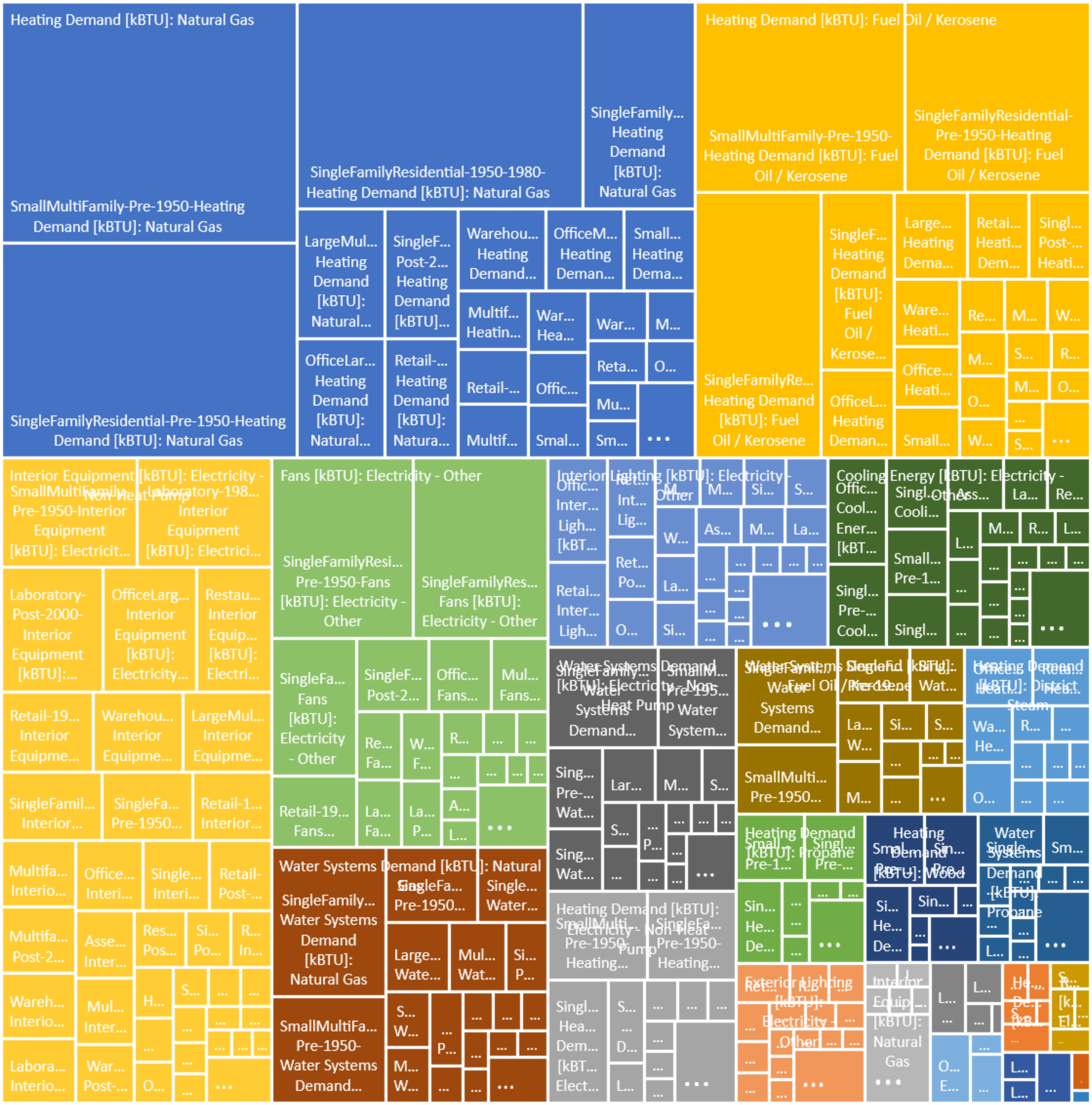


Table 16. Top 6 building-vintage prototypes for sector-wide energy savings. Savings are relative to ECM1. 3% Discount Rate, 30-year payback

Largest Technical Potential							Lowest Costs		
	Typology	Vintage	Electricity Savings Technical Potential		Electricity Savings Cumulative Potential		Typology	Vintage	$/kWh/ sf/year
			TWh	%	TWh	%			
ECM4	Single Family	Pre-1950	2.8	22%	2.8	22%	Hospital	1950-1979	$0.33
	Single Family	1950-1979	2.5	20%	5.3	42%	Hospital	1980-1999	$1.11
	Small Multifamily	1950-1979	1.8	15%	7.1	57%	Hospital	Post-2000	$1.32
	Single Family	1980-1999	1.0	8%	8.1	65%	Laboratory	1950-1979	$2.74
	Single Family	New Construction	0.5	4%	8.6	69%	Single Family	Pre-1950	$2.86
	Single Family	Post-2000	0.4	3%	9.0	72%	Restaurant	1950-1979	$3.28
ECM3	Single Family	Pre-1950	2.1	27%	2.1	27%	Hospital	1950-1979	$2.48
	Single Family	1950-1979	1.8	23%	3.9	50%	Single Family	Pre-1950	$3.44
	Small Multifamily	1950-1979	1.2	15%	5.0	65%	Hospital	Post-2000	$4.37
	Single Family	1980-1999	0.5	7%	5.6	72%	Hospital	1980-1999	$4.92
	Office (Large)	1950-1979	0.2	3%	5.8	75%	Single Family	1950-1979	$5.56
	Single Family	Post-2000	0.2	3%	6.0	78%	Restaurant	1950-1979	$6.56
ECM2	Single Family	Pre-1950	1.7	37%	1.7	37%	Single Family	Pre-1950	$3.13
	Single Family	1950-1979	1.3	29%	3.0	66%	Single Family	1950-1979	$5.90
	Small Multifamily	1950-1979	0.6	13%	3.6	79%	Hospital	1950-1979	$6.46
	Single Family	1980-1999	0.3	6%	3.9	85%	Small Multifamily	Pre-1950	$9.10
	Single Family	Post-2000	0.1	3%	4.0	88%	Hospital	Post-2000	$10.16
	Single Family	New Construction	0.1	3%	4.1	91%	Small Multifamily	1950-1979	$11.00

This analysis emphasizes two things. First, the largest potential of energy efficiency is older small residential homes. Second, more aggressive efficiency actions are just as cost effective as basic energy efficiency, despite higher costs. This underscores and emphasizes the need for financing and subsidies that encourage efficiency at all levels.

Figure 38. Energy use by typology and end use, grouped in colors by end use.



The *Limited Energy Efficiency* pathway of the *Energy Pathways Report* had 6.7 TWh more of electric space and water heating compared to the All Options benchmark decarbonization pathway. With every unit of efficiency deferred, more renewable generation, transmission and distribution costs were required, increasing systems costs. While *the Energy Pathways Report* and this Buildings Sector analysis take different approaches to modeling building energy demand and emissions, the near sector-wide application of ECM1 is analogous to assumptions underlying the *Limited Energy Efficiency* pathway. Further, this additional demand exceeds the technical potential of ECM2, suggesting that more aggressive retrofits the (e.g., ECM3 or ECM4) would be needed to achieve the 6.7 TWh relative reduction represented in the All Options pathway. The following section explores the implications of such different levels of energy efficiency using the building level data to construct a bottom-up pathway.

6 Existing Building Sector-Wide Decarbonization

6.1 Sector Pathway

The ECM Packages defined in Section 5.1 describe varying levels of interventions in residential and commercial buildings starting with electrification of systems, equipment and appliances and incrementally introducing building envelope interventions and increased levels of efficiency associated with the electrified systems, equipment and appliances. As such, the ECM packages provide a toolkit of performance levels for each building type. While the application of a singular ECM package can be scaled up to the sector level for contextualizing within the broader energy system – as presented in the prior section – the individual ECM packages are not intended to represent sector-wide decarbonization scenarios. However, their implementation in combination can be used elucidate the magnitude of change needed across the building stock necessary to achieve a decarbonization target such as identified in the All Options pathway.

This section explores three different combinations of ECM packages to create illustrative pathways to 2050 in order to explore the transition in the building stock. The reference pathway extends current technology and market trends, with partial adoption of more efficient systems and building shells occurring at a rate consistent with the natural turnover of equipment and building stock. Two additional pathways accelerate the pace, and deepen the level, of improvements to building energy performance. The assumptions underlying these pathways are defined in Table 17. These reflect the pace of change likely required to meet the Commonwealth's decarbonization goals based upon the analysis conducted in the *Energy Pathways Report* and do not reflect a specific set of policy interventions or market dynamics.

Table 17. Pathway Definitions.

Reference	Anticipated improvements in building energy mechanical and thermal shell systems based on natural stock turn-over and existing market and programmatic efforts. The reference case includes adoption of a Net Zero code for new construction in 2030.
Deep Retrofit Pathway	Deep retrofit approach accelerated combination of highly efficient electrification with improved building mechanical system and thermal shell efficiency improvements. 73% of buildings in 2050 have received at least some element of a buildings shell upgrade (ECM2-4). This pathway is analogous to the *Energy Pathways Report's* All Options Pathway
Electrification-Only Pathway	Electrification approach, with less emphasis on improvements to the building's thermal shell. This pathway is analogous to the *Energy Pathways Report's* Limited Efficiency Pathway. Only 19% of buildings in 2050 have received a buildings shell upgrade (ECM2-4)

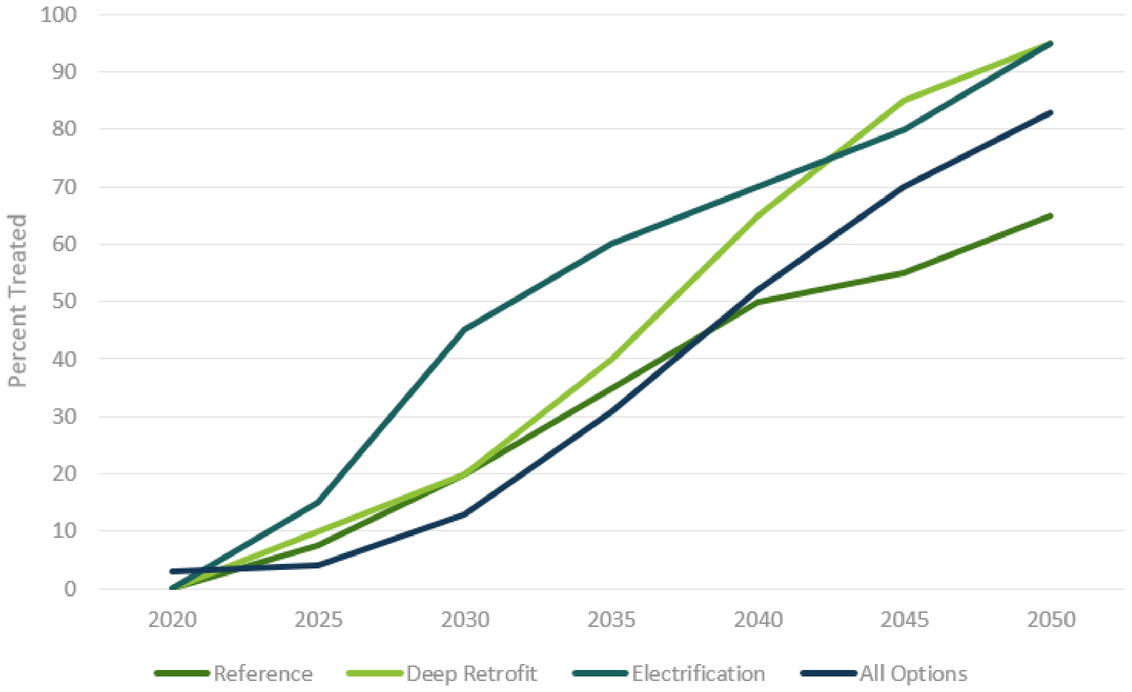
These pathways help to elucidate the potential tradeoffs associated with different sector-wide strategies. The deep retrofit pathway combines highly efficient heat pump-based heating and cooling systems with significant improvements to building envelopes, through comprehensive air sealing, insulation higher than current code, heat and energy recovery ventilation and high-performance windows. The deep retrofit pathway also assumes an accelerated and deeper level of adoption for these retrofits, when compared against the natural turnover pace represented in the reference case.

As an alternative approach, the electrification pathway has lower levels of improvements to building envelope performance. In comparison to the deep retrofit pathway, the electrification pathway relies more on the improved efficiency of mechanical heating and cooling systems and on the use of decarbonized electricity in place of fossil fuels, to reduce emissions. In the electrification scenario, the overall pace of adoption is also more rapid than in the reference and the deep retrofit pathways.

Due to differences in the bottom-up ECM evaluation approach and the top-down buildings sector representation taken in the *Energy Pathways Report*, it is infeasible to generate a 1:1 match with the pace of electrification and efficiency. However, we aim to replicate that here with blend of the ECM packages to illustrate the needed depth of action.

Figure 39 illustrates the variations in the pace and depth of adoption across the three pathway scenarios analyzed, along with a comparison to the *Energy Pathways Report* All Options pathway. The vertical axis represents the share of the total building stock that has undertaken building performance upgrades.

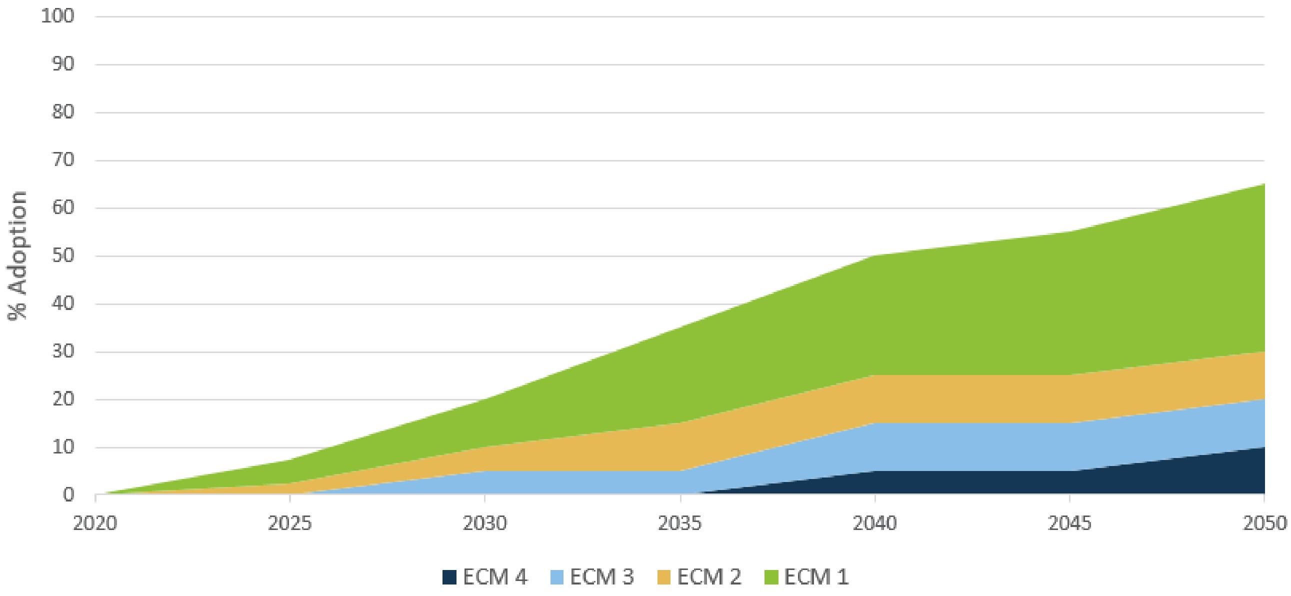
Figure 39. Cumulative share of buildings with performance upgrades by pathway.



Reference Case

The reference case estimates the levels of building energy performance and reductions in emissions that can be expected, based on natural turnover and current market trends and initiatives. Based on natural stock turnover rates by 2050, 65% of the building stock is expected to be upgraded Figure 40. These upgrades are most likely to be electrification only (ECM1), with a smaller number of deeper shell measures (ECM packages 2-4).

Figure 40. Adoption Rate of Energy Conservation Measure (ECM) packages over time in the Reference Case.



Key assumptions that informed the reference case included:

- Existing building turnover and renovations using the adoption schedule listed in Table 18.
    - Single family and small multifamily buildings assumed to have a 3% annual renovation rate. For the first five years retrofits are assumed to be a mix of ECM 1 and ECM 2, with ECM 1 being most common as it has the lowest barriers to implementation. ECM 3 and 4 start being adopted after 2025 and 2035 respectively. By 2050 65% of buildings have been retrofitted, with more than one half of these being ECM package 1.
    - Large Multifamily residential and commercial buildings have a slower rate of turnover with an assumed 2% annual renovation rate, and the same mix of ECM adoption as for single family and small multi-family.
- New construction 2017-2030. During the first decade of the modeling period 50% of new construction was assumed to be at baseline new construction efficiency which has enhanced building shell performance but maintains a mix of fuel types including new natural gas. Half of the new construction during this period adopts building electrification measures.
- The reference scenario includes all-electric high-performing new building policy adopted in 2030. After 2030 new building stock was assumed to be completed at the level of ECM package 3. After 2040 new construction was assumed to be at the level of ECM package 4.

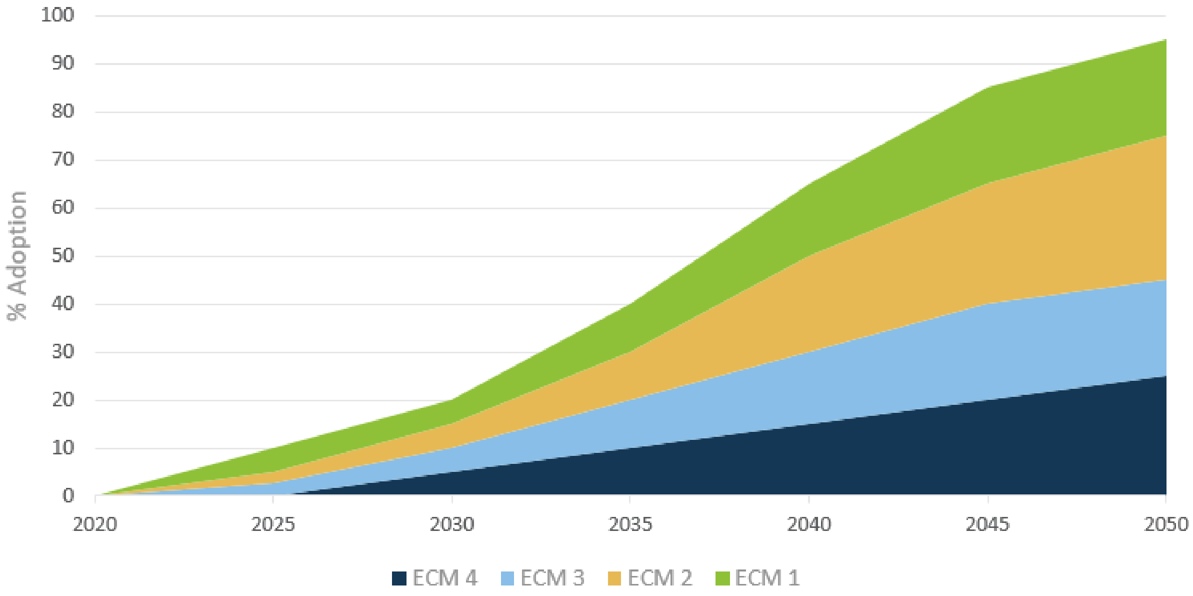
Table 18. Reference Case Adoption Rates 2020-2050 for existing buildings.

	No Action	ECM Package 1	ECM Package 2	ECM Package 3	ECM Package 4	Buildings Touched
2020	100	0	0	0	0	0
2025	92.5	5	2.5	0	0	7.5
2030	80	10	5	5	0	20
2035	65	20	10	5	0	35
2040	50	25	10	10	5	50
2045	45	30	10	10	5	55
2050	35	35	10	10	10	65

Deep Retrofit

The deep retrofit pathway assumed that, by 2050, 95% of the building stock has been upgraded with a relatively evenly distributed combination of ECM packages 1-4 (Figure 41). The deep retrofit approach combines the impacts of high efficiency mechanical systems with significant upgrades to building thermal shell performance.

Figure 41. Adoption Rate of Energy Conservation Measure (ECM) packages over time in the Deep Retrofit Pathway.



Key assumptions that informed the Deep Retrofit Pathway scenario include:

- Starting in 2020 a relatively even mix of ECM Packages 1-3 is adopted at a schedule defined in Table 19. After 2025 ECM Package 4 also starts being adopted. The deep retrofit pathway is characterized by a more even distribution of the ECM packages and, therefore, includes a deeper set of building shell upgrades than the electrification and reference scenarios.

- ECM Package 1 adoption was applied primarily for buildings constructed after 2000, under the assumption that this vintage had well performing envelops suitable to support electrification and with little opportunity for additional thermal performance gains. Building energy codes since 2000 have produced higher performance building envelopes, and therefore shell improvements in these buildings tend to be less cost effective than for older buildings.
- ECM Package 2 adoption was adopted primarily by Pre-2000 existing buildings. These buildings benefit the electrification of systems, equipment and appliances and from increased building envelope performance.
- ECM Package 3 adoption was projected for existing buildings and for new construction in the decade from 2020-2030. which generally aligns with energy code building envelope performance with high efficiency electrification.
- ECM Package 4 adoption starts in 2025 and grows to be 25% of total by 2050. This package has the highest building envelope performance with the highest efficiency electrification.

Table 19. Deep Retrofit Adoption Pathway Adoption Rates 2020-2050.

	No Action	ECM Package 1	ECM Package 2	ECM Package 3	ECM Package 4	Total Buildings Touched
2020	100%	0%	0%	0%	0%	0%
2025	90%	5%	2.5%	2.5%	0%	10%
2030	80%	5%	5%	5%	5%	20%
2035	60%	10%	10%	10%	10%	40%
2040	35%	15%	20%	15%	15%	65%
2045	15%	20%	25%	20%	20%	85%
2050	5%	20%	30%	20%	25%	95%

Electrification Pathway

The Electrification Pathway was more heavily weighted to emphasize building electrification, with lower levels of improvements to building shell performance. It should be noted that the electrification of the space conditioning systems with heat pumps is a significant improvement in a buildings final energy demand efficiency, even if the thermal load has not been significantly reduced. The adoption rates and the mix between the ECM packages for existing buildings in the Electrification Pathway are shown in Table 20. The Electrification Pathway also has a faster pace of adoption during the 2020s. Key assumptions that informed the Electrification Pathway case are illustrated in Figure 42 and include:

- Rapid adoption in the existing building sector of ECM package 1, at rates that exceed natural stock turnover. By 2030, 45% of received a performance upgrade, approximately one-quarter of which have received a building shell upgrade (ECM packages 2-4).
- By 2050 95% of all buildings have been upgraded, with nearly 80 percent of these being ECM package 1. Of the remaining upgrades half are ECM 2 and the remaining portion is shared equally by ECM packages 3 and 4.
- In New Construction, three quarters of new buildings are assumed to have performance consistent with 2020 new construction standards in 2020 with the remaining having one of the four ECM package upgrades. By 2050, roughly one half of the newly constructed buildings have ECM package treatment with the most common level being ECM package 3.

Figure 42. Adoption Rate of Energy Conservation Measure (ECM) packages over time in the Electrification Pathway

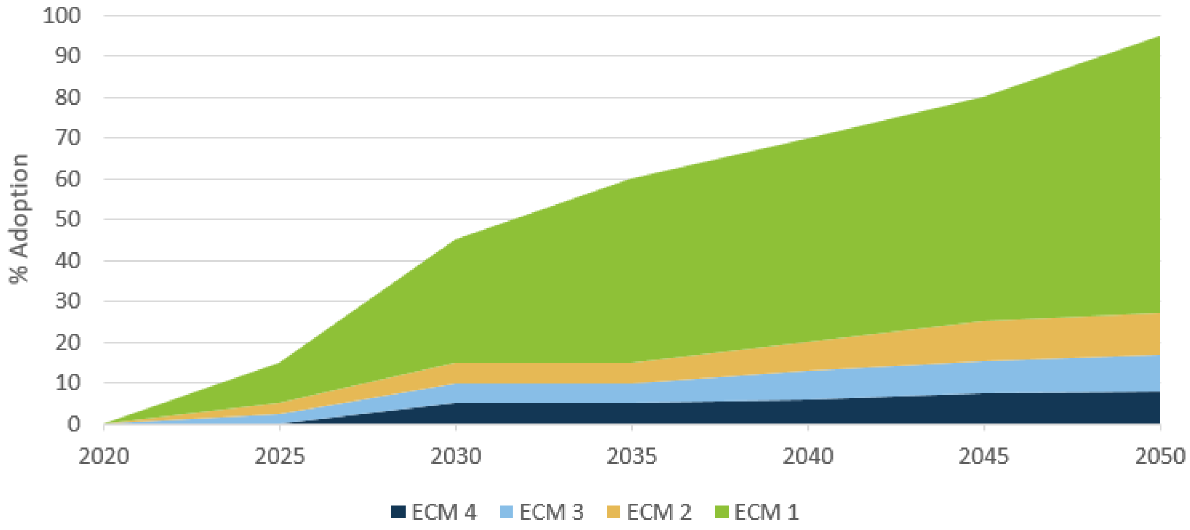


Table 20. ECM package adoption rates in existing buildings.

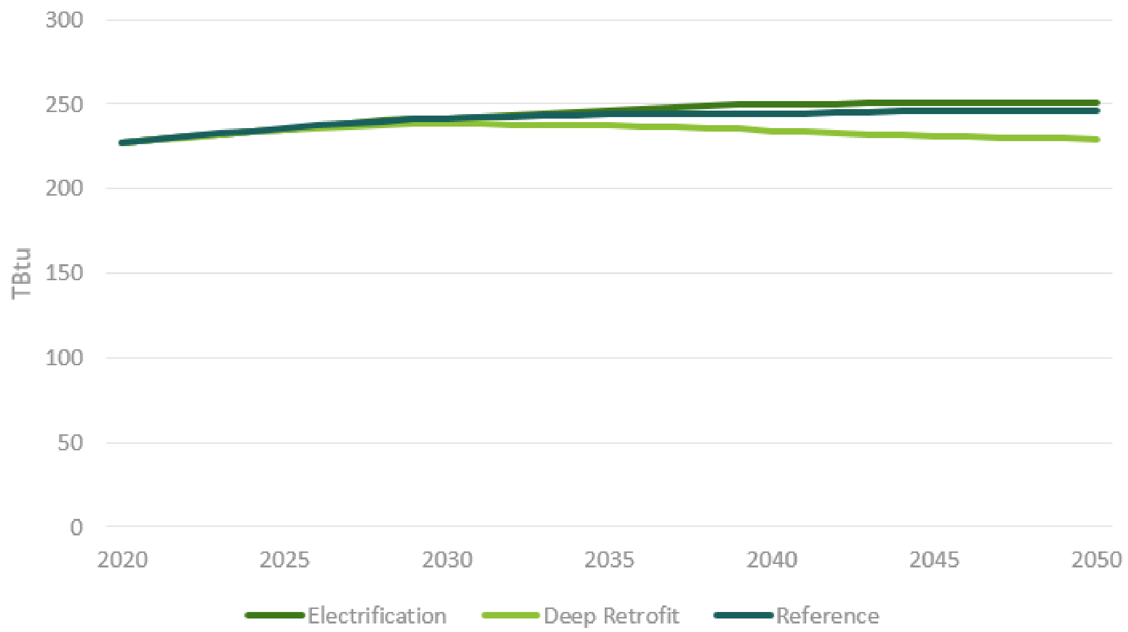
	No Action	ECM Package 1	ECM Package 2	ECM Package 3	ECM Package 4	Buildings Touched
2020	100	0	0	0	0	0
2025	85	10	2.5	2.5	0	15
2030	55	30	5	5	5	45
2035	40	45	5	5	5	60
2040	30	50	7	7	6	70
2045	20	55	9.5	8	7.5	80
2050	5	68	10	9	8	95

6.2 Sector Pathway Results

Residential Buildings

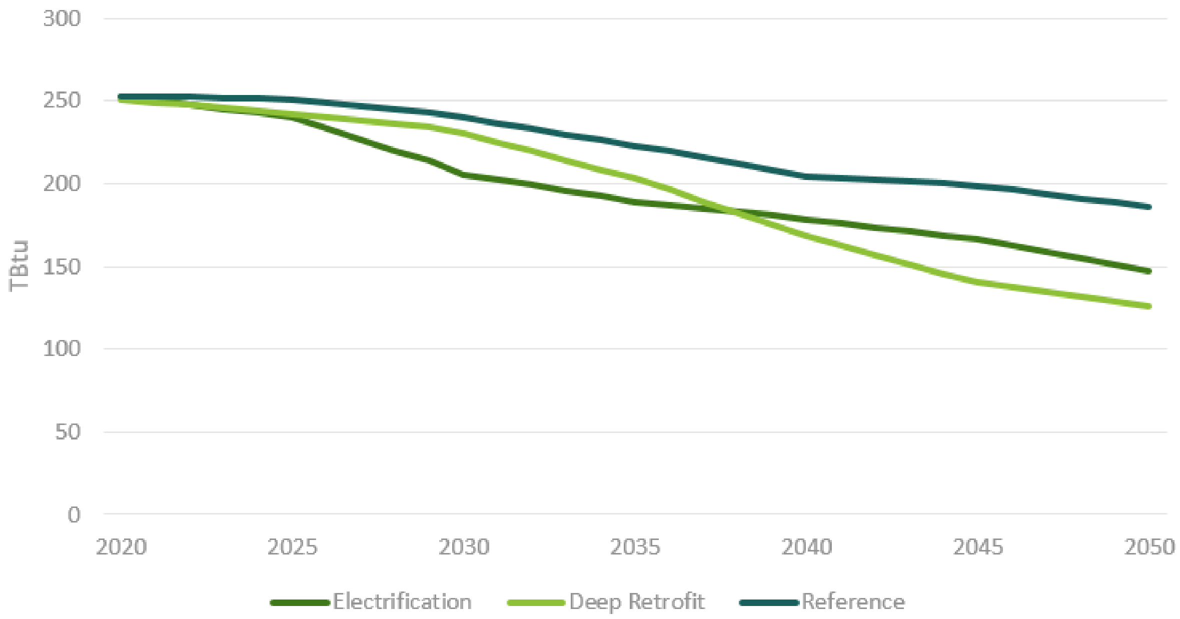
Residential building stock across the pathway scenarios is expected to grow from 4.3 billion square feet in 2020 to 5.3 billion square feet by 2050. As the sector's footprint grows according to economic and demographic drivers, the useful or service energy demand of buildings is also expected to grow, but at a slower rate than the square footage, as buildings become more efficient. Useful energy demand grows roughly 10% for the reference and electrification scenarios, while increasingly slightly for the deep retrofit scenario. Figure 43 illustrates the anticipated growth of useful energy demand by scenario.

Figure 43. Residential Buildings Total Useful Energy Demand by Pathway.



While the useful energy demand for residential buildings increases slightly, the efficiency of the systems used to meet those needs is expected to increase dramatically as heat pumps, which operate to move heat to or from a building with an efficiency greater than 100%, replace combustion-based equipment. Thus, while a growing housing stock is expected to increase the useful energy demand for the building sector in the coming decades, Figure 44 illustrates a decline in the final energy demand for all three scenarios.

Figure 44. Residential Buildings Total Final Energy Demand by Pathway.



The Residential Sector in the Electrification Pathway shows a 42% reduction in final energy demand for residential buildings, from from 252 TBtu in 2020 to 147 TBtu in 2050. The Deep Retrofit Pathway reduces final energy demand by 50%, reaching 126 TBtu in 2050. The largest reduction in energy by end use is associated with the heating and domestic hot water end uses (Figure 45).

Figure 45. Residential Final Energy Demand by End Use, Electrification Pathway (left) and Deep Retrofit Pathway (right). Fans represent energy required for HVAC forced air systems.

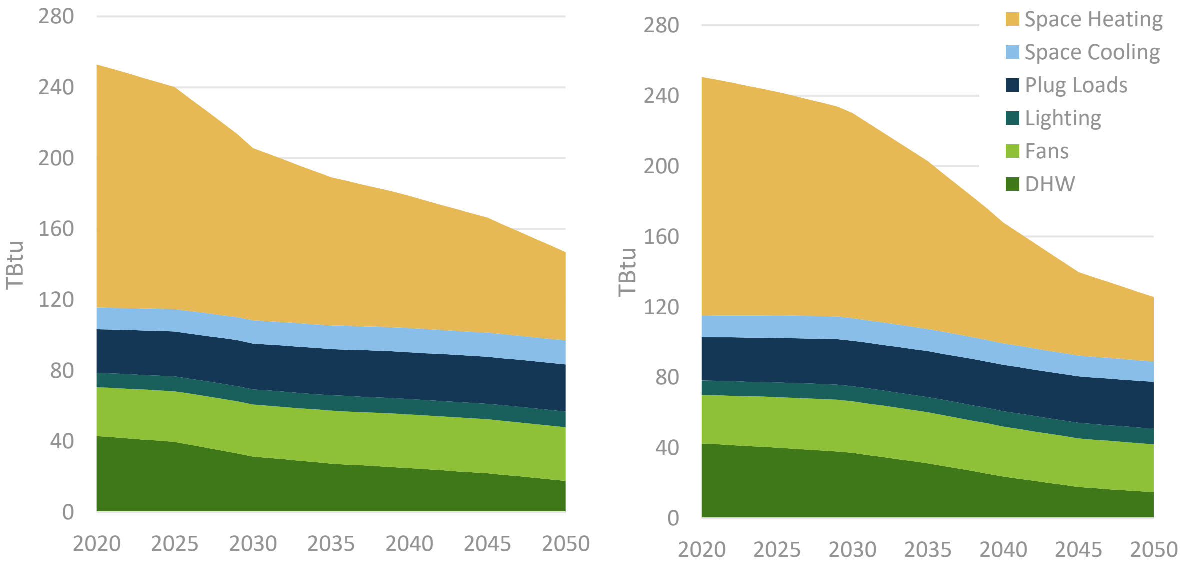
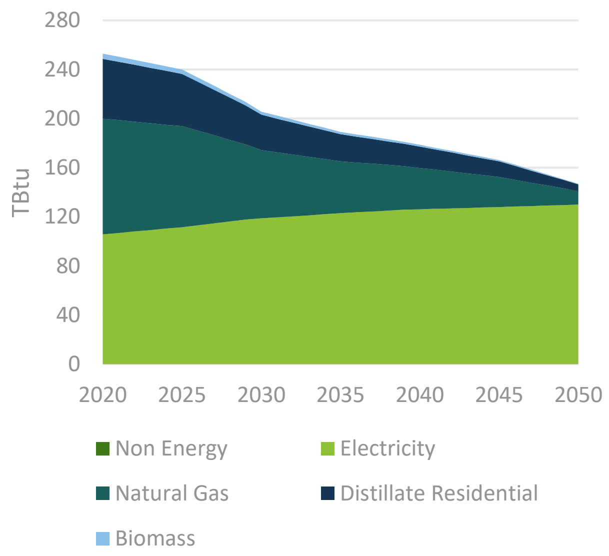


Figure 46 illustrates the same level of final energy demand, by fuel type. As end uses are electrified the portion of final energy demand met by natural gas and distillate fuel oil declines dramatically.

Figure 46. Residential Buildings Final Energy Demand by Fuel, Electrification Pathway (left) and Deep Retrofit Pathway (right).



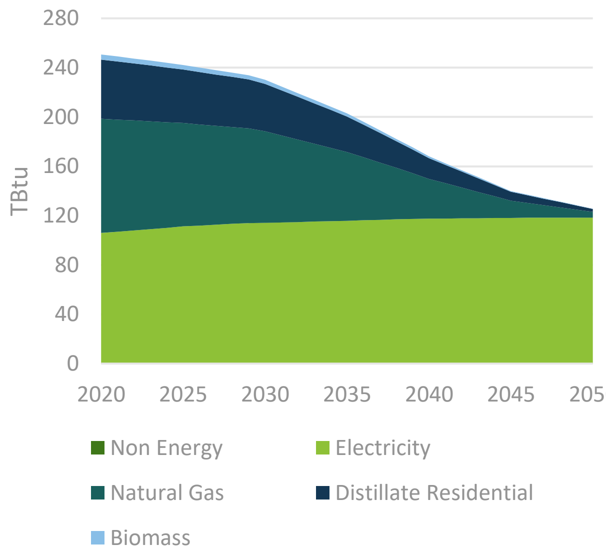


Figure 47 demonstrates the effect of a greater number of envelope improvements on energy demand for space heating in the Deep Retrofit pathway relative to the Reference and Electrification pathways. This lowers electricity demand overall in relation to both the Reference and Electrification pathways (Figure 48).

Figure 47. Residential Buildings Useful Energy for Space Heating over Time by Pathway

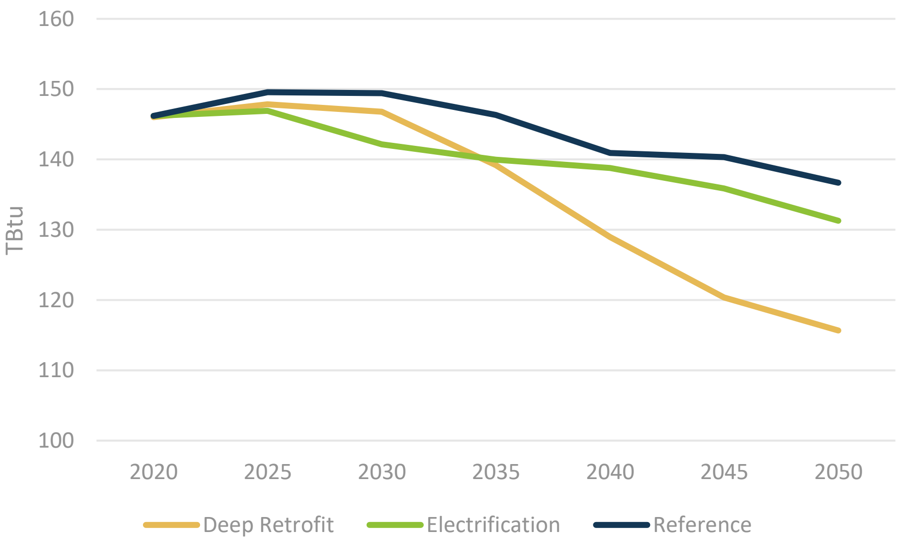
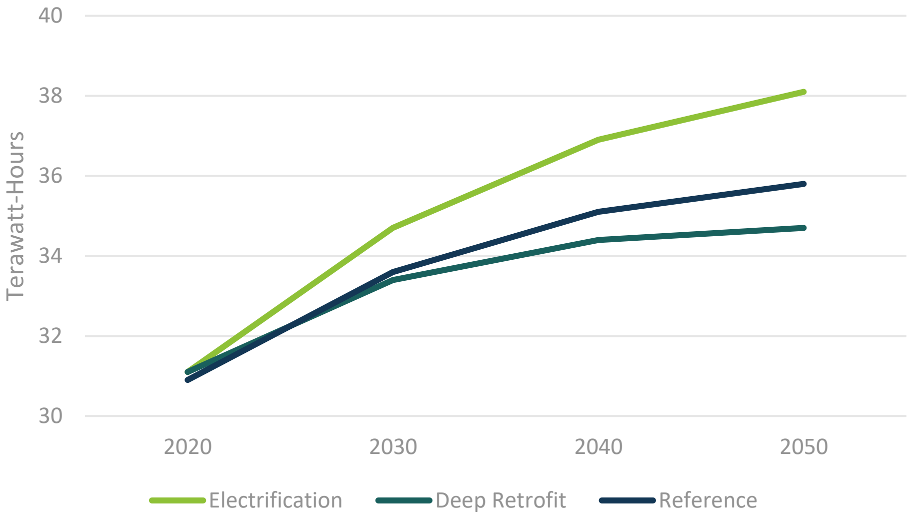


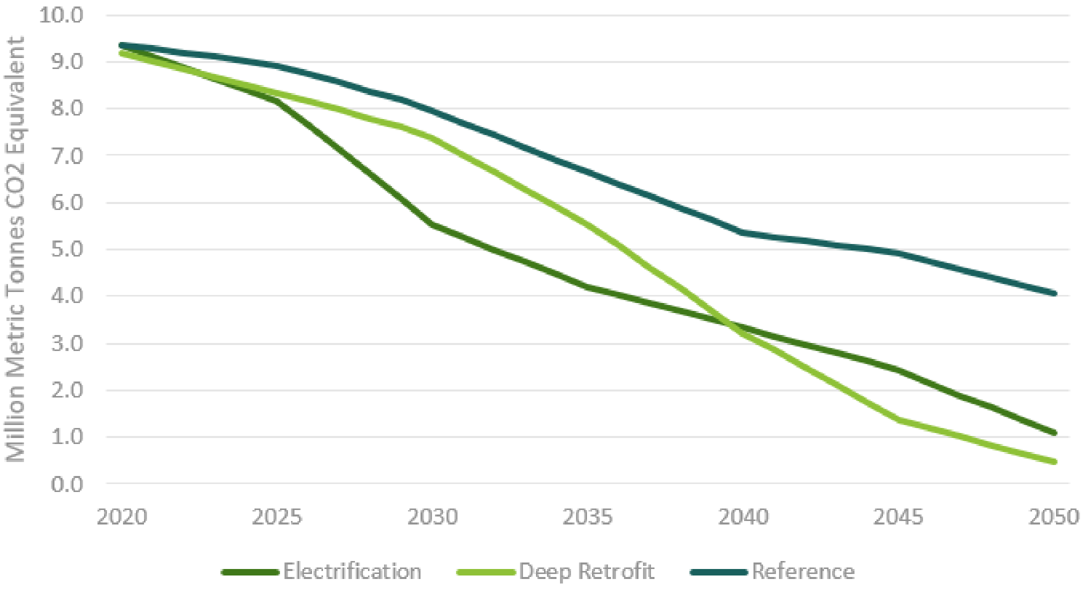
Figure 48. Electricity Demand for Residential Buildings over Time by Pathway



6.2.1 Residential Buildings Emissions Reductions

Emissions from the residential building sector are driven by the final energy demand and the composition of the fuels used to meet that demand. As the electric supply is increasingly based on renewable sources, the electrification of building heating and cooling systems will reduce sector emissions. Figure 49 illustrates projected annual emissions for residential buildings, also highlighting the earlier reductions projected for the Electrification Pathway.

Figure 49. Residential Buildings Annual On-Site Emissions by Pathway.



The analysis results in total emissions from residential buildings declining from 9.3 million metric tonnes per year in 2020 to 1.07 million tonnes in 2050. By 2050 the Pathway avoids a cumulative total of 60 million tonnes in comparison to the reference case. Below, Figure 50 illustrates the reduction from Residential buildings from

2020 to 2050. Most of the anticipated emissions reductions are derived from single family and small multi-family buildings, the largest portion of the building stock.

Figure 50. Annual Residential On-site Emissions by Building Type, Electrification Pathway (left) and Deep Retrofit Pathway (right).

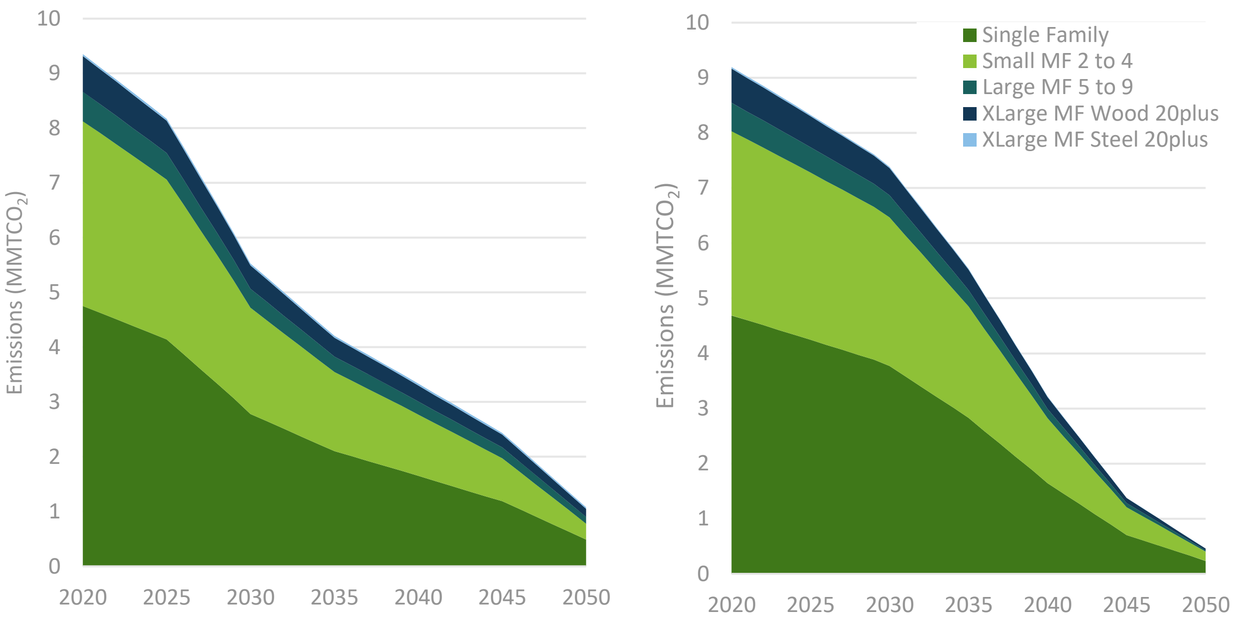
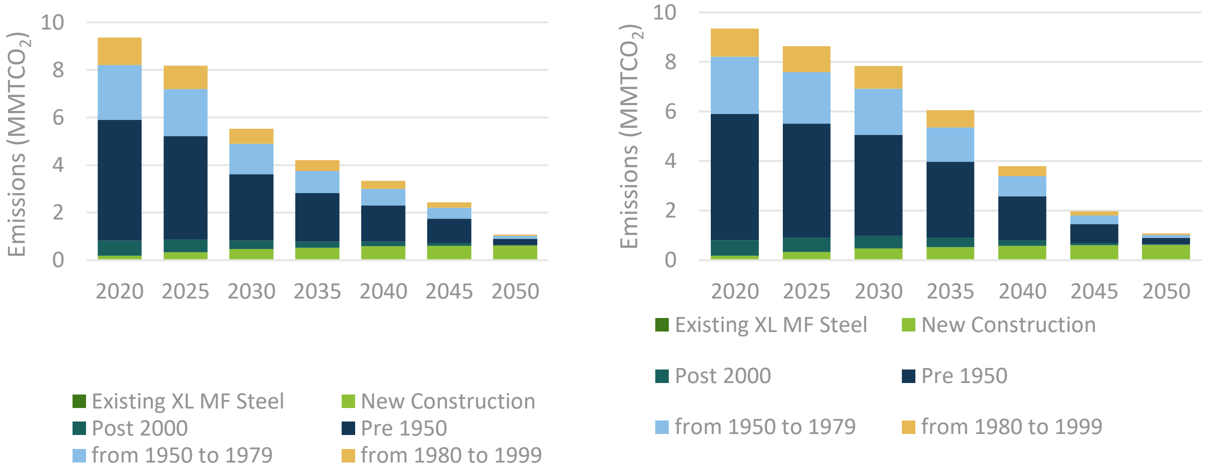


Figure 51 below shows emissions reductions by residential vintage illustrating most of the emissions reductions come from Pre-1950 residential buildings.

Figure 51. Annual Residential Buildings Emissions by Building Vintage, Electrification Pathway (left) and Deep Retrofit Pathway (right). Note under these scenarios the enactment of a Net Zero code does not occur until the 2030's leading to a relatively higher contribution of the new building stock later in 2050.



Attaining this level of reductions requires a simple annual average of 90,000 retrofits for existing buildings and 7,000 high performance new construction units from 2020 through 2050 (Figure 52).

Figure 52. Residential Buildings Cumulative Number of Retrofit and High-Performance New Construction Units, Electrification Pathway (left) and Deep Retrofit Pathway (right).

By 2050 in the Electrification and Deep Retrofit analyses, 90% of existing buildings have been retrofitted. Figure 58 above shows this results in a 90% reduction in greenhouse gas emissions from 2020. Both the Electrification and Deep Retrofit pathways reduce emissions primarily based on electrification. Electricity demand is reduced by increased application of more aggressive retrofits in the Deep Retrofit pathway.

Noticeably, buildings built before 1950 produce the largest share of the emissions (55%) while only making up 43% of the total existing building stock (Table 21). The share of households is much lower than the share of emissions for the pre-1950 vintage, meaning total annual emissions per household is much higher. On average a pre-1950 household produces 4.18 Metric Tonnes of CO_2e annually, which is more than double the emissions from a post-2000 vintage home, and 40% more than an average home built between 1950-1979. While, the greatest efficiency gains will come from retrofitting pre-1950s households, still 90% of all existing households across all vintages will need to be electrified and retrofitted between 2020-2050 to meet the 2050 GHG reduction targets, but the information here may be useful to set targets for policy implementation and timing of building stock retrofits.

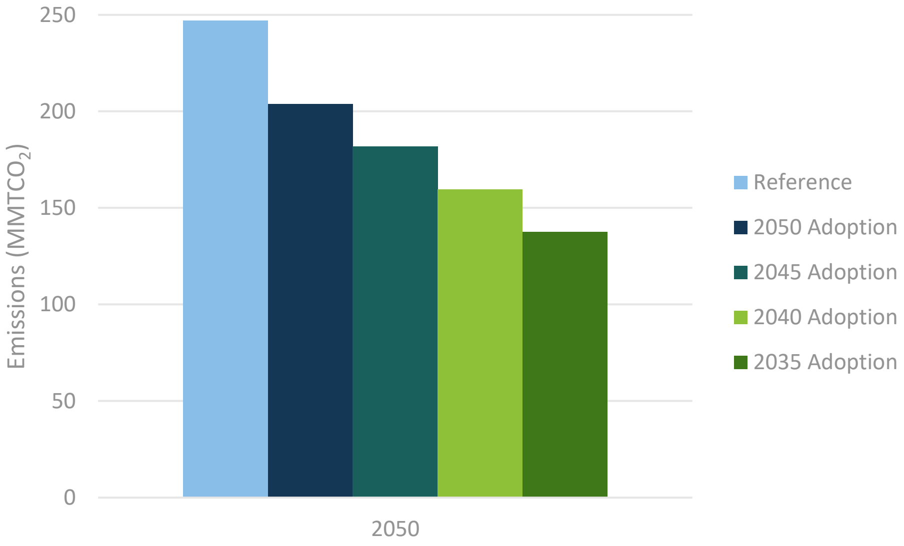
Table 21. Number and Share of Households and Residential Emissions by Vintage.

Building Vintage	Share of Emissions 2020	Share of Households 2020	Total Households 2020	Total 2020 emissions ($MMTCO_2$e) / household
Pre-1950	55%	43%	1,210,000	4.18
1950-1979	25%	28%	787,000	2.90
1980-1999	13%	18%	522,000	2.27
2000-2016	7%	11%	311,000	2.05

6.2.2 Acceleration of a Residential Building Performance Standard

The Electrification scenario is based on the adoption of building retrofits during the coming three decades that is faster than natural turnover rates, particularly in the first decade, but is then relatively steady, with emissions declining at a similar steady pace. An illustrative building performance standard adoption analysis in this study uncovers the impacts of accelerating the adoption of a building performance standard to compare benchmarks. Performance standards are a type of buildings energy and emissions regulation that set an upper limit to building energy use and emissions. The Building Performance Standard was set to compare effects of retrofitting 90% of existing buildings by 2035, 2040 and 2045. The results in Figure 53 show that adopting a performance standard earlier, reduces the cumulative emissions in 2050; for example, adoption by 2035, has the potential to reduce cumulative emissions by 50 million tonnes by 2050 compared to the Electrification scenario; This trend would hold true if the standard were adopted before 2035 as well. To achieve these additional reductions would require 180,000 annual retrofits to existing buildings between 2020 and 2035, roughly doubling the number of households retrofit each year in comparison to the 90,000 per year in the Electrification analysis.

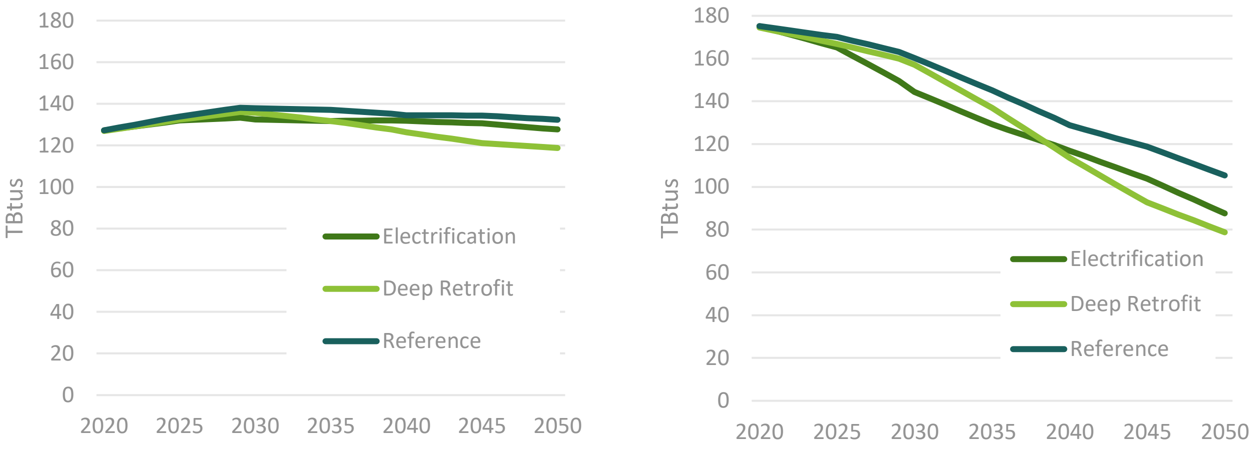
Figure 53. Residential Buildings Cumulative Emissions by 2050 for Alternative Timings of Building Performance Standard Adoption, Electrification Pathway.



6.2.3 **Commercial Buildings**

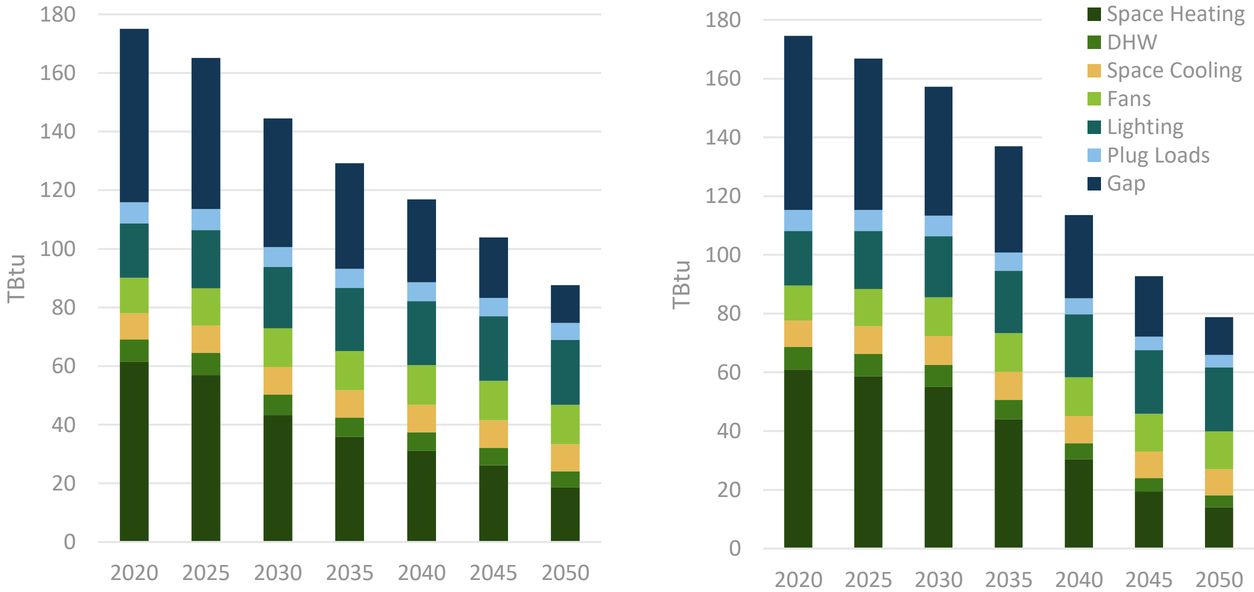
Commercial building stock in the Commonwealth is expected to grow from 1.3 billion square feet in 2020 to 1.7 billion square feet by 2050. As the sector's footprint grows due to economic and demographic drivers the useful energy demand of buildings is also expected to grow, but at a slower rate than the square footage, as buildings become more efficient. Useful energy demand for commercial buildings grows for all three scenarios through 2030 due to anticipated economic growth, and remains roughly steady for the reference scenario, while declining for the deep retrofit and electrification scenarios. Figure 54 illustrates the anticipated growth of useful energy demand and final energy demand by scenario.

Figure 54. Commercial Buildings Useful Energy Demand (left) and Final Energy Demand (right) by Scenario.



From 2020 to 2050, the total useful energy demand for commercial buildings is expected to increase through 2030 and then decline modestly through the remainder of the analysis period. Commercial buildings constructed before 1980 account for the largest share of useful energy demand. While Small Simple and Large Complex commercial buildings are responsible for nearly 60% of the total energy demand. Final energy demands for commercial buildings decline between 45% for the reference scenario and 62% for the deep retrofit scenario as illustrated in Figure 55. The more rapid decline in final energy use compared to the useful energy demand is due to conversion of fossil fueled combustion-based systems to high efficiency heat pumps to meet space conditioning needs.

Figure 55. Commercial Final Energy Demand by End Use, Electrification Pathway (left) and Deep Retrofit Pathway (right).



The decrease in final energy demand between 2020 and 2050 illustrates that efficiency and electrification, along with building energy control strategies contribute significant energy savings in commercial buildings, with advanced heat pump-based heating and cooling providing largest impacts. This pattern is more pronounced for the commercial sector than it was for the residential sector in large part because of the additional savings realized from energy management. Note that by 2050 the final energy demand is less than the useful energy demand, indicating that the overall efficiency for this sector increases to more than 100% as the major end uses take advantage of highly efficient heat pump-based technologies.

Space heating is the largest contributor to the energy load in commercial buildings comprising nearly 1/3 of the total final energy demand. Optimizing space heating by setting proper setbacks when buildings are unoccupied, has the potential to significantly reduce the energy load, but these measures can also be applied to lighting and ventilation. Lighting and fans required to meet ventilation code make up the next largest segment of demand. Ventilation demands are likely higher with the increased focus on indoor air quality and higher outdoor air rates in the COVID-19 pandemic; however, this study did not take that into account as the analysis was done before any data on indoor air quality and building use was available.

The shift to electricity to meet final energy demands across the commercial building stock is illustrated in Figure 56, and the relative changes in electricity demand is shown in Figure 57. Notably, only about 1 TWh separates the Electrification and Deep Retrofit pathways.

Figure 56. Commercial Buildings Final Energy Demand by Fuel, Electrification Pathway (left) and Deep Retrofit Pathway (right).

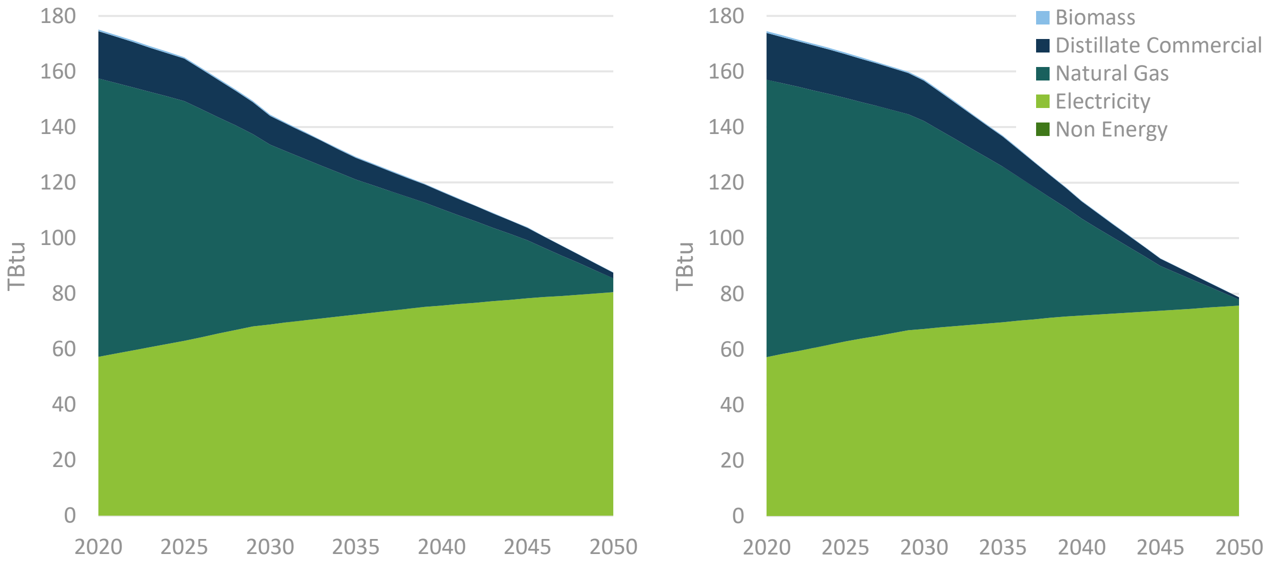


Figure 57. Commercial Electricity Demand by Pathway

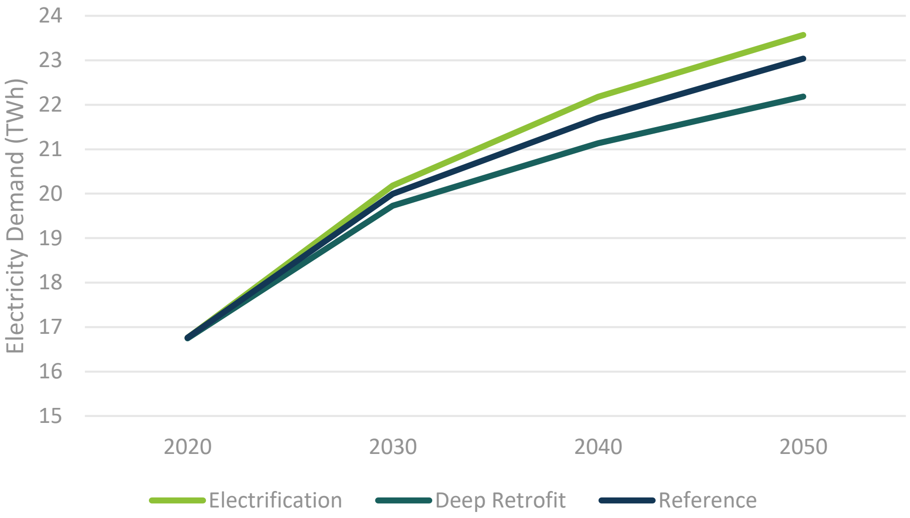


Figure 58 illustrates the annual emissions reductions for the Pathway scenarios, with reductions in annual emissions by 2050 of more than 90% for the Deep Retrofit and Electrification Pathway and 75% for the Reference Pathway.

Figure 58. Commercial Buildings Annual Emissions by Pathway.

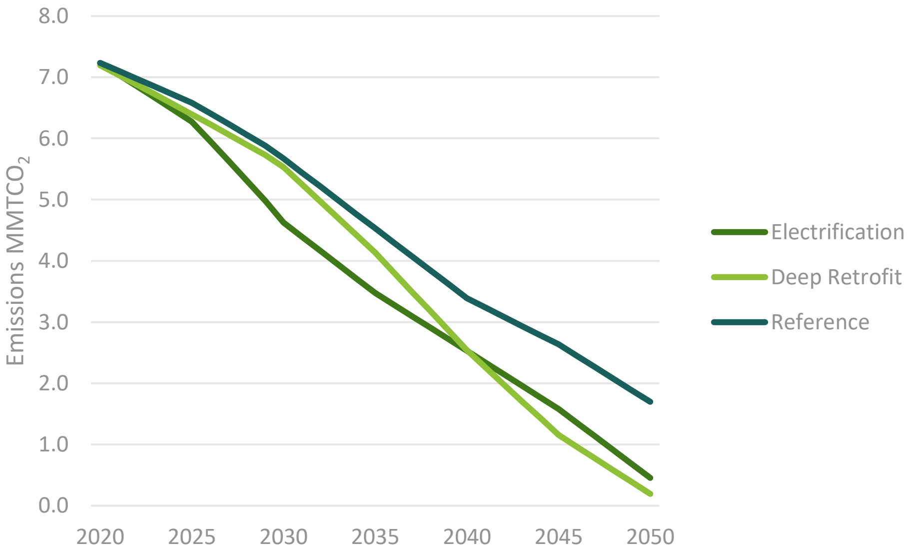


Figure 59 and Figure 60 show emission by building type and vintage. The 'Gap' segment is utilized to model unaccounted natural gas from the building sector models to align with the 2016 EIA data. These include various processes, such as processing heating or backup systems, that were not easily captured in the building types represented in this study yet make up another large segment of the total energy load. It is assumed that those fuels will slowly become electrified or decarbonized. The building types dominating emissions continue to be the small simple and large complex commercial buildings. Pre-1980 vintage buildings continue to contribute the most to emissions, and thus have the potential for the greatest reductions in energy use and emissions.

As seen in the residential subsector, both the Electrification and Deep Retrofit pathways reduce emissions primarily based on electrification. Electricity demand is reduced by increased application of more aggressive retrofits in the Deep Retrofit pathway.

Figure 59. Commercial Buildings on Site Annual Emissions by Building Type, Electrification Pathway (left) and Deep Retrofit Pathway (right).

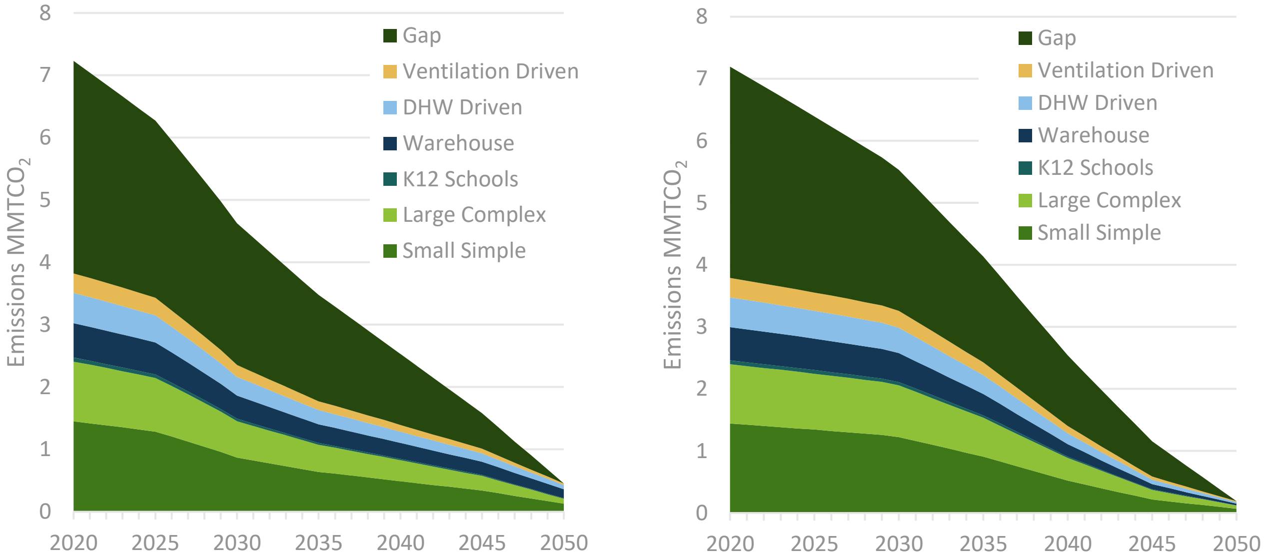
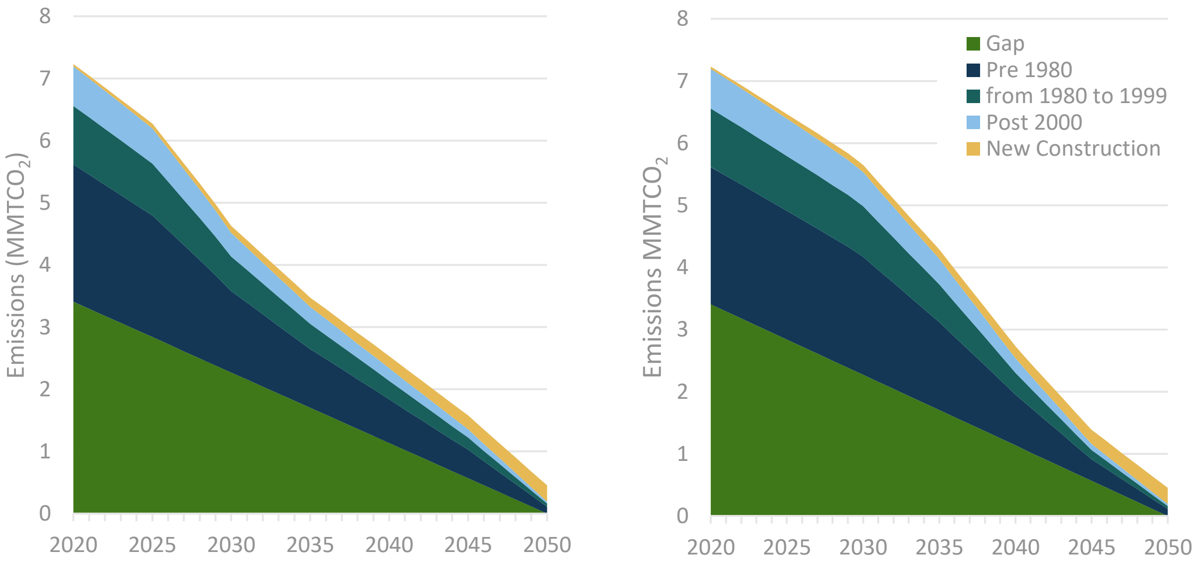
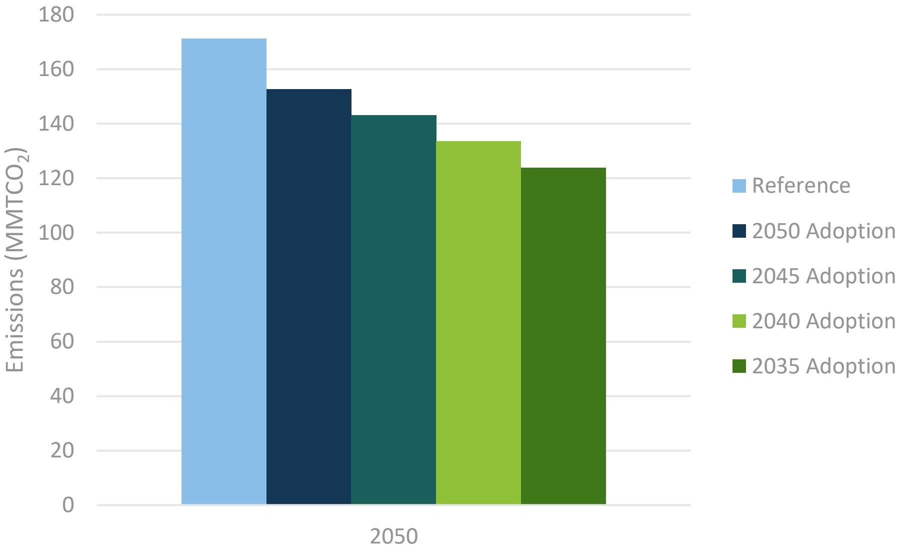


Figure 60. Commercial Building on Site Annual Emissions by Vintage, Electrification Pathway (left) and Deep Retrofit Pathway (right). Note under these scenarios the enactment of a Net Zero code does not occur until the 2030's leading to a relatively higher contribution of the new building stock later in 2050.



6.2.4 Acceleration of Commercial Buildings Retrofits via a Simulated Performance Standard

Figure 61. Cumulative Emissions from Commercial buildings by 2050 with adoption of a Building Performance Standard in 2035, 2040, 2045 or 2050; Electrification Pathway.



A buildings performance standard was modeled for different implementation years, 2035, 2040, 2045 and 2050 to study impacts of accelerated implementation on emissions and energy use commercial buildings. As shown in Figure 61, the cumulative emissions in 2050 decreases more than 10% for implementation of a building performance standard in 2050, and as much as 30% for 2035 implementation.

Of the nearly 1.3 billion square feet of the existing commercial buildings, approximately 95% will need to have some level of retrofit by 2050 to achieve the emissions goals, with roughly 40% receiving ECM 1 level retrofits which primarily focus on improving the building systems, approximately 50% receiving ECM 2 level retrofits that include additional thermal shell measures and only 5% receiving deeper building performance retrofits.

A building performance standard implemented in 2050 would require 42 million square feet of commercial building space retrofitted annually, with roughly 18 million square feet receiving ECM 1 and 22 Million square feet receiving the ECM 2 retrofit annually. Implementation of a commercial building performance standard in 2035 would require an annual retrofit double that of 2050 implementation (approximately 84 million square feet of commercial retrofits on average annually). In doubling the annual rate of retrofit, a threefold savings of total cumulative emission over the 2020-2050 timeframe can be achieved.

Appendix A. Land Use Codes used in Typology Mapping

Table 22. MAPC land use codes per study typology.

Typology	Land Use Code Used
Single Family Residential	101
Small Multifamily	013[i], 031[ii], 104, 105, 121[iv], 122[iv], 123[iv], 124[iv], 125[iv], 304[v], 306[v]
Large Multifamily (5-19 Stories)	013[i], 031[ii], 111[iii], 121[iv], 122[iv], 123[iv], 124[iv], 125[iv]
Large Multifamily (Wood Construction) (20+ Stories)	013[i], 031[ii], 111[iii], 121[iv], 122[iv], 123[iv], 124[iv], 125[iv]
Large Multifamily (Steel Construction) (20+ Stories)	013[i], 031[ii], 111[iii], 121[iv], 122[iv], 123[iv], 124[iv], 125[iv]
Office	031, 140, 340, 341, 342, 350, 352, 353, 354, 355, 356, 402, 900, 931, 935, 957, 985
Hospital	305, 913, 955, 979
Lab	404
Convention/Assembly	037, 931, 954, 960
Hotel	300, 301, 302
Restaurant	326
Retail	013[i], 031[ii], 321, 322, 323, 325, 330, 331, 332, 333, 334, 335, 336, 337, 338
School (K-12)	351, 934, 940, 941
Supermarket	324
Industrial	316, 400, 401
Warehouse	316, 401

[i] Segmented to a small multifamily, large multifamily or retail typology based on attributes in the land use data

[ii] Segmented to a small multifamily, large multifamily, retail or office typology based on attributes in the land use data

[iii] Segmented to a more specific large multifamily typology based on attributes in the land use data

[iv] Segmented to a small multifamily or large multifamily typology based on attributes in the land use data

[v] Segmented to a large multifamily typology based on attributes in the land use data

Appendix B. Detailed Description of ECM Packages

Table 23. Description of ECM packages applied to Single Family and Small Multifamily typologies.

Single Family and Small Multifamily			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 2.73		Heat Pump DHW Heating UEF: 3.2	Heat Pump DHW Heating UEF: 3.45
Envelope			
None	R-60 Roof/Attic	Window U-value: 0.25	R-30 Walls
	R-15 Walls	Window SHGC: 0.32	Window U-value: 0.21
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window SHGC: 0.24
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**Demand-Control Ventilation**	ECM 2	ECM 2
	70% Effective Energy Recovery		
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 24. Description of ECM packages applied to Large Multifamily typologies.

Large Multifamily (5-19 Stories), Large Multifamily (Wood Construction) (20+ Stories), Large Multifamily (Steel Construction) (20+ Stories)			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 2.73		Heat Pump DHW Heating UEF: 3.2	Heat Pump DHW Heating UEF: 3.45
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 25. Description of ECM packages applied to Small and Medium Offices, Retail, and Supermarket Small and Simple typologies.

Office (Small), Office (Medium), Retail, Supermarket			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 2.73		Heat Pump DHW Heating UEF: 3.2	Heat Pump DHW Heating UEF: 3.45
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 26. Description of ECM packages applied to Large Office and Convention/Assembly typologies.

Office (Large), Convention/Assembly			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 2.73		Heat Pump DHW Heating UEF: 3.2	Heat Pump DHW Heating UEF: 3.45
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	ECM 1	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 27. Description of ECM packages applied to the K-12 School typology.

School (K-12)			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 4		Heat Pump DHW Heating UEF: 4.5	Heat Pump DHW Heating UEF: 5
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 28. Description of ECM packages applied to Hospital and Laboratory typologies.

Hospital, Laboratory			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 20	ECM 1	ECM 1	ECM 1
Heat Pump Space Heating HSPF: 10			
Heat Pump DHW Heating UEF: 100% efficient			
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
		Window SHGC: 0.35	R-30 Walls
		Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to ECM 3
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Heat Recovery Chiller			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 29. Description of ECM packages applied to Hotel and Restaurant typologies.

Hotel, Restaurant			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 4		Heat Pump DHW Heating UEF: 4.5	Heat Pump DHW Heating UEF: 5
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

Table 30. Description of ECM packages applied to the Warehouse typology.

Warehouse			
ECM 1 Electrification	ECM 2 Low Efficiency	ECM 3 Medium Efficiency	ECM 4 High Efficiency
	ECM 1 plus:	ECM 2 plus:	ECM 3 plus:
Systems			
Heat Pump Cooling SEER: 15	ECM 1	Heat Pump Cooling SEER: 20	Heat Pump Cooling SEER: ECM 3
Heat Pump Space Heating HSPF: 9		Heat Pump Space Heating HSPF: 10	Heat Pump Space Heating HSPF: ECM 3
Heat Pump DHW Heating UEF: 100% efficient		Heat Pump DHW Heating UEF: 3.2	Heat Pump DHW Heating UEF: 3.45
Envelope			
None	R-30 Roof/Attic	Window U-value: 0.38	R-40 Roof/Attic
	R-15 Walls	Window SHGC: 0.35	R-30 Walls
	Airtightness to 0.4 CFM/sf at 0.3 in. wc.	Airtightness to 0.2 CFM/sf at 0.3 in. wc.	Window U-value: 0.22
			Window SHGC: 0.25
			Airtightness to 0.1 CFM/sf at 0.3 in. wc.
Controls			
Setbacks to 70°F and 75°F in heating and cooling, respectively	**ECM 1**	ECM 1	ECM 1
Demand-Control Ventilation			
70% Effective Energy Recovery			
Appliances			
Electric conversion	ECM 1	ECM 1	ECM 1

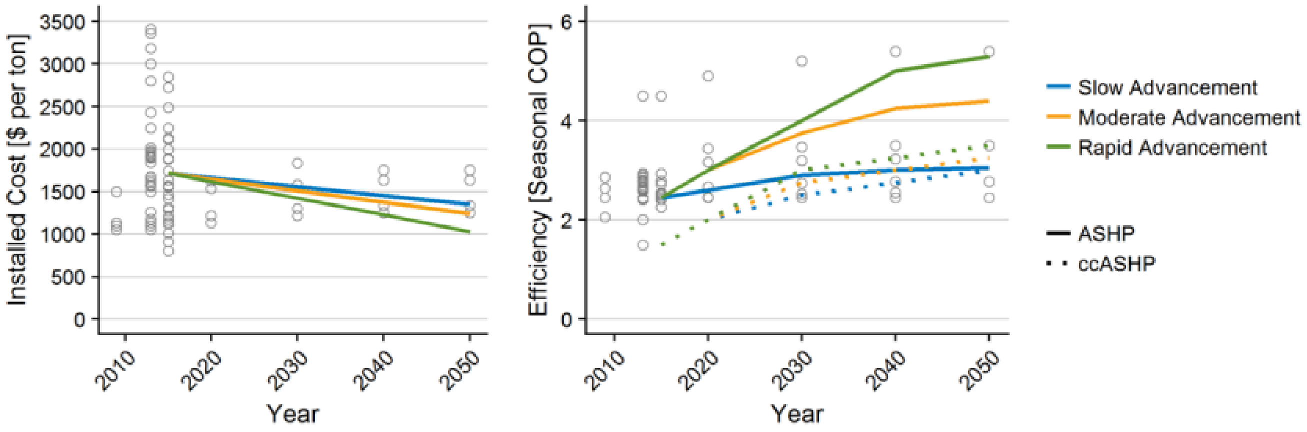
Appendix C. Technology Profiles

This appendix provides additional details on technologies discussed throughout the report.

Air-Source Heat Pumps (ASHP)

Highly efficient "cold climate" ASHPs have gained a foothold through the Northeast over the past decade. These widely available systems are rated to maintain high levels of efficiency and capacity even in sub-zero temperatures. ASHPs on the market today range from a seasonal Coefficient of Performance (COP) of approximately 2.2 – 3.5. This represents an equivalent efficiency of 220-350% compared to fossil fuel furnace and boiler efficiencies, which range from 65-99% efficiency. Even with a significant efficiency head start, heat pumps will likely continue to improve: NREL's Electrification Futures Study (EFS) report projects that seasonal heat pump performance for residential ASHPs may improve by almost 70% while their cost may decrease by over 40% by 2050 (Figure 62).

Figure 62. Installed unit costs (left) and performance projections (right) for residential ASHPs for space heating applications. Dots indicate data from literature, and lines show projections developed in this analysis. Cold climate ASHP is denoted by ccASHP. Source: NREL Electrification Futures Study



ASHP technologies can be configured to serve a wide variety of building heating and cooling distribution systems. Air-to-air heat pumps condition air through a central air handler or run refrigerant to distributed conditioning units (such as wall-mounted units, console units, or short-run ducts) located throughout a building. Air-to-water heat pumps condition water which is then distributed to baseboards, console units, or radiant coils in a building. Variable refrigerant flow (VRF) heat pump systems, which primarily serve larger buildings and can have the capability for zone-to-zone heat recovery, have been gaining popularity and growing at a compounded annual growth rate of 11% since 2015.[56] These VRF systems function primarily in an air-to-air configuration.

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[56] ACHR News. *VRF Market Expected to Hit $24 Billion by 2022.* 2017. https://www.achrnews.com/articles/134465-vrf-market-expected-to-hit-24b-by-2022

Ground-Source Heat Pumps (GSHP)

Currently, GSHPs only account for about 10% of nationwide heat pump installations (EFS). Their lower prevalence is due to their relatively high initial capital cost, land use requirements, and extended construction schedule. Over the past 15 years, GSHP systems have predominantly transitioned to closed loop systems, away from open loop systems that consume groundwater. Closed loop systems typically circulate a water/antifreeze mixture through plastic tubing that is buried in the ground or submerged in water. A heat exchanger transfers heat between the refrigerant in the heat pump and the buried loop.[57] With the advent of closed loop systems, the number of applications for which GSHPs are feasible has increased and the Commonwealth has seen an increase in these systems in the past decade. In cold climates, GSHPs outperform ASHPs by about 45% in heating, and 30% in cooling when accounting for seasonal effects.[58]

Domestic Hot Water Systems

While nationally about 45% of residential water heaters are electric (RECS 2009), in Massachusetts, that is only 20% of homes with electric resistance water heaters, and heat pump water heaters (HPWH) represented only 1% of the market. HPWHs have efficiencies 3.0-3.5 times greater than electric resistance-based water heaters and are currently eligible for incentives under Mass Save when replacing an electric resistance water heater. Given water heating is one of the largest end-uses in residential buildings, second only to space heating, there is ample opportunity to cost-effectively both electrify this end use and decrease the electricity consumed by installing HWPHs instead of the standard electric resistance. The Electrification Futures Study also predicts that costs for HPWH are expected to drop by 50% and seasonal efficiency is expected to improve by as much as 60%. In the commercial sector, HPWH have not yet gained traction due to their relatively high cost. Such systems may be advantageous in buildings with simultaneous heating and cooling demands such as commercial laundries, hotels, and restaurants. Solar hot water heaters also have an opportunity to provide hot water with minimal emissions. While solar hot water is likely to be used in supplemental applications, it’s currently cost effective against electric and natural gas water heaters in some cases.

Building Envelope Efficiency

For small residential buildings, top and bottom air sealing, improved insulation, weather-stripping openings, efficient LED lighting, ENERGY STAR certified appliances and smart thermostats are typical measures. The Mass Save program already provides incentives for most of the efficiency strategies identified above, though not at the required levels indicated by our analysis. For example, the home insulation program can cover 75-100% of qualifying insulation costs with no incentive limit.[59] In commercial buildings, energy efficiency strategies typically include lighting, installing variable frequency or speed drives on fans and pumps, energy recovery, replacement of heating, cooling, and air handling equipment, and addition or commissioning of DDC controls. While there are likely some efficiency opportunities in all buildings, older buildings and those that have not implemented energy efficiency measures in the past 10-15 years, are likely to have a wider range of savings opportunities.

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[57] U.S. Department of Energy. *Energy Savor: Heat Pumps.* https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems/geothermal-heat-pumps

[58] Passive House Alliance. https://www.phius.org/NAPHC2016/Jacobson GSHP ASHP.pdf

[59] Massachusetts Save. *Save on Home Insulation*. https://masssave.com/en/saving/residential-rebates/home-insulation

Demand Management and Demand Response

There are numerous demand management and demand response programs currently available in Massachusetts and ISO-NE. Demand response systems react to signals provided by ISO-NE to reduce load during time of peak grid congestion or loading, whereas demand management systems operate to limit demand charges for a specific site. In New England, in C&I buildings, demand charges typically makeup at least half of a facility's electrical charges, with the rest of the bill charged based on the actual energy used over the month. Demand charges are typically based on the peak electrical use (demand) during a 15-minute window during daytime hours each month. This charge is levied to help recoup the costs for infrastructure which must be retained to allow the customer to use this demand. Demand charges are currently typically not charged during nighttime hours since the grid is relatively lightly loaded.

Demand response and demand management systems are generally operated by demand response program aggregators and are not accessible to the typical small or medium scale consumer for several reasons. First, many customers with small loads – such as residential customers – are billed on rate schedules which do not include a demand component, therefore enrollment in a demand management program would not reduce monthly electricity charges. Second, the overhead required to enroll and administer a site in a demand response program makes enrollment of small systems (less than a few hundred kilowatts) currently impractical. Although such programs have, and continue to be, effective at reducing overall utility demand during peak periods, there are large parts of the Massachusetts consumer base who cannot participate in these markets because of the overhead required for market enrollment. Future developments, such as new market pricing signals, advanced metering infrastructure (AMI), broader adoption of time-of-use rates, proliferation of distributed generation, energy storage and electric vehicles, and new end-user technologies could provide opportunities for wider consumer adoption and a smarter grid for increased demand management.

Advanced Metering Infrastructure (AMI)

AMI or smart meters are utility grade meters that are able to measure near-real time energy consumption and store or communicate that consumption data to the utility. While they can be on gas or electrical meters, they are typically used for electric meters. AMI meters collect energy data, ranging from seconds to hourly, allowing utilities to implement dynamic pricing to optimize the grid, as well as allowing customers and the utility insights into building energy use patterns. Widespread rollout of AMI will enable the adoption of new pricing signals. For example, electricity rates could vary based on the carbon content of the grid (marginal pricing), when dirtier generation sources are brought online, electricity prices could increase to drive a change in user behavior. Through the integration of AMI, flexible loads on-site within a building could adjust to the increased price and ramp-down or shut-off entirely. Similarly, a signal could be broadcast during periods of peak load, which is current operation of demand management, or at times of low-renewable electricity generation to reduce load, and local energy systems could react appropriately.

Flexible Load Technologies

Systems such as water heaters, energy storage, HVAC, and particularly EV charging are prime examples of existing technologies which are already able to interface with demand management systems. Although current enrollment in demand response programs is very small in Massachusetts, it is anticipated that enrolling these systems in demand management programs will become commonplace in the coming decades. Furthermore, newer technologies such as smart appliances for refrigerators, dishwashers, lighting, and laundry machines, are likely to expand and are discussed in more detail below.

Today, most larger commercial and industrial utility customers who are currently enrolled in a demand response program, turn to building systems such as lighting and HVAC to reduce load upon receipt of a demand response signal from the utility provider. Oftentimes, this is a manual process (e.g. a phone call to register the event), but automatic control also exists. These systems are often used in demand response programs because small changes in HVAC or lighting setpoints are often undetectable by occupants, and the systems already include the centralized controls and processors via a building automation system necessary to act on a demand response signal. This allows facility managers and building owners to take advantage of the revenue opportunities presented by enrolling in a demand response program without inconveniencing the building's users. However, the benefits of these systems are somewhat limited due to the small range of adjustability and load reduction (often 10-20%), and the need for a complex, central system to implement the commands. With the continued proliferation of building automation systems and development of smart capabilities, these systems are expected to be commonplace over the coming years. It is also anticipated that an HVAC system using predictive algorithms, or with external communication capabilities, will know a demand response signal is coming, and could pre-cool a space, or top up a thermal storage system such that it could reduce load even further during the demand response event, resulting increased demand savings. On the residential side, smart thermostats are already large measures in utility programs throughout the country. With more heating moving towards electric, the opportunity for flexible HVAC to have electric grid benefit also grows.

The continued adoption of electric vehicles provides another opportunity for load flexibility. Currently incentives are available for electric vehicle (EV) chargers which are internet connected and enrolled in a demand response program.[60] This program pays users a set incentive for allowing their EV charging to be curtailed during periods of high demand. In addition to this, most EVs come with the ability to schedule charging so that the battery is charged during times of low grid congestion. However, these systems need to be manually set, and may only be used if there is a financial reward for the user. By providing additional communications, and/or time-of-use (TOU) pricing, EVs could communicate with the electricity grid, and pre-schedule charging at times when electricity prices are low, grid carbon content is low, or grid demand is low. As the EV market grows, it will be important for building codes, rate structures, and incentive programs to help capture this potential. For example, new building codes and/or state EV incentives could require connectivity and controllability for all high voltage EV charging. Furthermore, future vehicle to grid (V2G), or vehicle to building (V2B) technologies are expected to become available to provide opportunities to selectively discharge the on-board battery to provide power to the grid or directly to the building based on needs. These technologies have the potential to help reduce grid demand, or to provide backup in the case of a grid outage.

Similar to the expected proliferation of EVs, it is likely that Massachusetts will see a significant increase in the number of battery storage systems by 2050. Today, Massachusetts is moving towards integrating battery energy storage systems with solar PV for large systems (>500kW) to help with grid peak management and intermittency of renewables generation. Battery storage systems continue to decline in price, prove their value

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[60] Eversource. *EV Home Charger Demand Response.* https://www.eversource.com/content/ema-c/residential/save-money-energy/explore-alternatives/electric-vehicles/ev-charger-demand-response

to the utilities in the form of grid support, and to end-users in the form of increased resilience. These benefits are likely to drive adoption, which would be further supported by more sophisticated energy pricing signals

Finally, the integration of smart appliances, such as dishwashers, refrigerators, and washing machines with connected buildings and homes will enable remote control of these devices based on factors like electricity cost and GHG emissions intensity of electricity, etc. By providing a dishwasher, for example, with real-time access to energy prices, the equipment can self-schedule to run at times that are most cost-effective to the owner. Such appliances will be able to monitor their energy usage and the associated costs, and provide real-time feedback to users such as cost and carbon savings available by deferring washing laundry to night-time or other off-peak hours. Real-time feedback to end-users in terms which have an impact, such as cost-savings, will help to incentivize end-user to make informed decisions.

Drop-in Renewable Fuels

There is a theoretical potential for decarbonization of buildings to occur though the replacement of fossil fuels with decarbonized drop-in fuels. In some cases, these actions would require little-to-no changes to the building systems and electric distribution infrastructure. Decarbonized methane, generated by biological, thermochemical, or electrochemical processes, could be processed to a grade that is compatible with existing equipment. Liquid fuel oil could be generated under thermochemical and electrochemical processes to a drop-in ready grade. Biodiesel may be currently be blended up to 20%. Higher blend levels may require equipment upgrades (storage tank, hoses, gaskets, burners etc.) due to the chemical differences between fossil heating oil and biodiesel.[61] Supplies of these fuels are considered limited and costly as discussed in detail above and in the *Energy Pathways Report*, but there may be a role to leverage such resources in some buildings and applications.

Building Hydrogen Technologies

Hydrogen could be used as alternative to natural gas or fuel oil to generate energy from combustion in both new and existing buildings. Hydrogen delivery and use in concept operates similarly to natural gas, but may require new distribution systems and equipment. There are several considerations to account for in a transition from natural gas to hydrogen at an individual building level including viability of existing piping, metering, safety, gas purity standards and conversion strategies, approaches, and phasing. Hydrogen is generally considered incompatible with metals due to hydrogen embrittlement and corrosion, thus polymer-based distribution would be needed. The bigger challenge to hydrogen conversion is the availability of hydrogen compatible appliances and equipment. Currently such equipment is in the early stages of development and is not likely to see widespread adoption until a significant hydrogen economy, which includes both supply and demand, exists. Hydrogen ready appliances – that can be modified to switch from natural gas to hydrogen on site – could be required or deployed.

Hydrogen blending into the natural gas system could alternatively serve as a more plausible use of hydrogen to partially decarbonize the natural gas system. Doing so would require identifying the maximum blend level for the existing distribution system and end uses. While a partial solution, such blending could be used to obtain compliance credits under a regulatory framework, the *Energy Pathways Report* shows that renewable

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[61] NREL. Biodiesel Handling and Use Guidelines. https://www.nrel.gov/docs/fy06osti/40555.pdf

hydrogen is unlikely to scale until the 2040s when sufficient renewable energy could produce hydrogen cost effectively. Even in such case, renewable hydrogen is mostly used in transportation applications under the assumption that building systems are too-costly to transition to hydrogen.

District Energy & Steam

District energy systems can vary greatly in terms of design, scale, and age in Massachusetts. Most serve campuses or urban cores. Older systems tend to use steam to transfer heat, while newer systems use more efficient hot water. Systems rely on the combustion, typically of a fossil fuel, to generate the heat carried by the steam or hot water to an end use. District systems leverage density to centralize heating generation and distribution with the aim of lowering costs. Decarbonization of existing systems, which mostly rely on combustion to generate steam or hot water, would require replacement using a drop-in renewable fuel or using an electric boiler. An efficiency gain could be achieved by upgrading some systems from steam to hot water, but this would require costly rebuilding of the entire distribution system. Despite its relative inefficiency at heating, steam delivers higher temperature heat that can be used in some industrial processes or for sterilization in hospitals and laboratories. To align with decarbonization efforts, new district systems would need to utilize a zero or very low emissions intensity heat source.

A recent study by the Home Energy Efficiency Team (HEET) proposes using a GeoMicroDistrict approach for neighborhood heating needs.[62] This approach would involve the deployment of a number of wells in a utility right-of-way to support ground-source heating and cooling for a neighborhood. This study helped to inform a proposal by Eversource to conduct a demonstration project within Massachusetts to assess the viability of such a model.[63] In the *Energy Pathways Report*, steam production in MA for district and industrial uses grew from 14 to 17 TBtu per year. This assumed that demand side switching to other processes would be too costly. Instead these systems installed a dual fuel boiler at their central plant that can use electricity or pipeline gas to make steam. Adding electric resistance to existing boilers is a relatively inexpensive step and that enhances system flexibly. This allows the steam generator or the district to take advantage of surplus low-cost and low-carbon electricity, which offsets the operating cost of increasingly expensive pipeline gas. This keeps marginal curtailment low thus allowing for the overbuilding of renewable generation to meet the needs of high demand days. Depending on the context, strategies to decarbonize new and existing district energy systems may provide some cost-effective and feasible mechanisms to reduce fossil fuel use and pursue efficiency and flexibility.

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[62] GeoMicroDistrict Feasibility Study. HEET MA (2019). https://heetma.org/wp-content/uploads/2019/10/HEET-BH-GeoMicroDistrict-Final-Report.pdf

[63] DPU Filing 19-120. https://d279m997dpfwgl.cloudfront.net/wp/2020/01/Initial_Filing_Volume_2_11-8-19.pdf