Investigating the Impacts of Climate Change on an Affordable Multifamily Building in Boston, Massachusetts

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ABSTRACT

Building energy codes are driving improved energy performance in new multifamily construction in Boston, Massachusetts, where Passive House certification is an approved compliance pathway. The energy modeling norm is to use Typical Meteorological Year weather files that are approximately 30 years old. But what happens when the 'cold-climate' Boston becomes more like the 'mixed-humid' climate of Memphis, TN, in 60 years? Do we need to rethink how buildings are modeled today? This study explores the impact of climate change on affordable multifamily housing design under three energy codes by modeling future climate scenarios to assess future energy consumption, evaluate building resilience during power outages, and analyze the effect on equity across tenants of different economic brackets.

Using tools to incorporate future weather datasets from established climate projection models, buildings with four levels of envelope construction and airtightness were analyzed under future climate scenarios. This study showed that climate change would impact cooling and heating consumption, resilience, and equity, suggesting the possible need to incorporate future weather data during the design process.

Introduction

In 2022, Massachusetts enacted a law[1] to reduce greenhouse gas (GHG) emissions by 85% compared to 1990 levels and establish a policy framework to achieve Net Zero GHG emissions by 2050 (EEA 2022). The Massachusetts (MA) Stretch Energy Code's 2023 update and the introduction of the Opt-in Specialized Code align with the State's 2050 policy objectives and are the basis for this study.

Boston adopted the Specialized Code, which took effect in January 2024. According to this new regulation, a new multifamily (MF) building that exceeds 12,000 square feet (ft^2) must be certified as Passive House. Data from the Passive House Institute US (PHIUS) Certified Project Database (PHIUS 2024) shows that the new Passive House MF in greater Boston exhibits Site Energy Use Intensity (EUI) ranging from 20 to 27 kilo British thermal units per square foot ($kBtu/ft^2$).[2] In contrast, existing MF constructed in Boston, built between 2008 and 2019, have an average site EUI of 56.4 $kBtu/ft^2$ (Simmons et al. 2022), indicating that Passive House MF in Boston may achieve a 52% to 64% improvement in energy performance over the existing MF.

The Passive House standard reduces energy usage and enables building electrification, thereby significantly decreasing GHG emissions. A key design strategy of Passive House is using high-efficiency heat pumps, which provide heating, cooling, and domestic hot water (DHW). Existing MF buildings have traditionally relied on centralized gas boilers for heating

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[1] An Act Creating a Next-Generation Roadmap For Massachusetts Climate Policy; https://malegislature.gov/Laws/SessionLaws/Acts/2021/Chapter8

[2] PHIUS provides information on certified projects on its database: https://www.PHIUS.org/certified-project-database

and DHW. The adoption of the Specialized Code represents a shift away from fossil fuel dependence and creates a pathway for full electrification for Boston's MF buildings.

However, the comparison of energy performance between Passive House MF and existing MF buildings is based on simulation results utilizing historical weather datasets and city-wide surveys without considering the impacts of climate change. Passive House and Specialized codes do not mandate forecasting future energy performance based on future weather datasets. Current energy analysis practice relies on historical weather files, specifically Typical Meteorological Year (TMY3) weather datasets, using a data format called EnergyPlus Weather (.epw). [3] Passive House MF may deliver better energy performance under TMY3 weather conditions. However, more studies are needed to determine whether Passive House MF will outperform conventional buildings with existing envelopes and construction in a future climate.

As climate change intensifies, Boston's traditionally cold climate might evolve to resemble the mixed-humid climate of Memphis, Tennessee, within the next 60 years (Fitzpatrick and Dunn 2019). The anticipated shift in future weather conditions could significantly affect buildings' energy usage. Specifically, in MA, where electricity costs are among the highest in the nation (U.S. Energy Information Administration 2024), the changing climate may further worsen the financial burden of utility costs. This study focused specifically on the impact of climate change on affordable multifamily (AMF) buildings, where many tenants are from underserved communities. These residents often lack the means and resources to independently mitigate the severe impacts of climate change and are more financially vulnerable.

Research Aim

This study aimed to achieve three primary objectives. First, this study investigated the impact of climate change on the energy performance and resilience of an AMF building in Boston using a real-world case study. The Boston Housing Authority (BHA) owns the case building, and it is designed to meet the energy performance standards of both the Passive House and the energy code (ASHRAE 90.1). Most existing AMF buildings lack Passive House-level envelope and airtightness. Therefore, evaluating both Passive House and existing envelopes for their performance in the context of projected climate change is crucial. This study analyzed four levels of envelope assemblies and infiltration rates: Case A - Passive House standard; Case B - Massachusetts Code minimum envelope (ASHRAE 90.1-2019); Case C - Existing building using Massachusetts Base Code envelope in 2010 (ASHRAE 90.1-2010); and Case D - Existing building with no envelope insulation.

This study focused on tenants' survivability and comfort by assessing the building's resilience, which is defined as its ability to maintain livable conditions during extreme outdoor temperatures and power outages under future climate scenarios.

Second, this study explored the impact of climate change on equity among AMF residents, where equity is defined as fair accessibility to affordable and efficient energy. This is crucial because the affordability of energy use relative to income levels influences the scalability of the broader goals of sustainability and decarbonization.

Third, this study intends to build capacity amongst modelers by explaining techniques for integrating future climate datasets into energy simulations. These datasets and tools commonly rely on the Coupled Model Intercomparison Project Phase 6 (CMIP6). The generation of future

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[3] The .epw (EnergyPlus Weather) file format is used by EnergyPlus, a building energy simulation program, to provide detailed weather data for modeling building energy performance. https://energyplus.net/.

climate datasets poses technical challenges for design teams, requiring expertise in climate science research to customize and adapt them to energy simulation software formats. Our research evaluates three methods based on freely available weather projection tools and future climate datasets, and we provide insights into our workflow for design teams lacking experience in handling future weather files.

Methodology

Current and future weather datasets

Building energy simulations are integral to confirming code compliance for MA AMF buildings. The accuracy of building energy simulations relies heavily on the quality of weather files utilized. The TMY3 dataset, derived from the record period from 1976 to 2005, is commonly used for energy simulations (Wilcox and Marion 2008).

Coupled Model Intercomparison Project (CMIP) is a global collaborative initiative within the World Climate Research Program (WCRP) that conducts climate change experiments and modeling (Michaut 2013). CMIP6 is the latest phase of CMIP, utilizing the most recent climate models and experiments for more precise climate projections. This study utilizes weather data from CMIP6. The CMIP6 researchers have developed a set of emission scenarios dictated by socio-economic assumptions. These are called Shared Socioeconomic Pathways (SSPs), as shown in Figure 1. These SSPs are associated with changing GHG emission levels and radiative forcing values, which result in variable degrees of global warming. The five scenarios included in CMIP6, ranging from the most optimistic (lowest impact) to the most conservative (highest impact and greatest warming), are SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5. This study utilized three different methods to obtain future weather files for Boston. We first used an R-based tool called ‘EPWshiftr’ (Jia, Hongyuan et al. 2023). To utilize EPWshiftr, we selected and downloaded the original climate change experiment datasets directly from the CMIP6 data repository servers by specifying a set of global attributes. Then, the files had to be modified in R to downscale the data structure before they could be used for energy simulations. EPWshiftr employs a popular method for downscaling CMIP6 data called morphing, first introduced by Belcher et al. (Belcher et al. 2005). This mathematical technique transforms

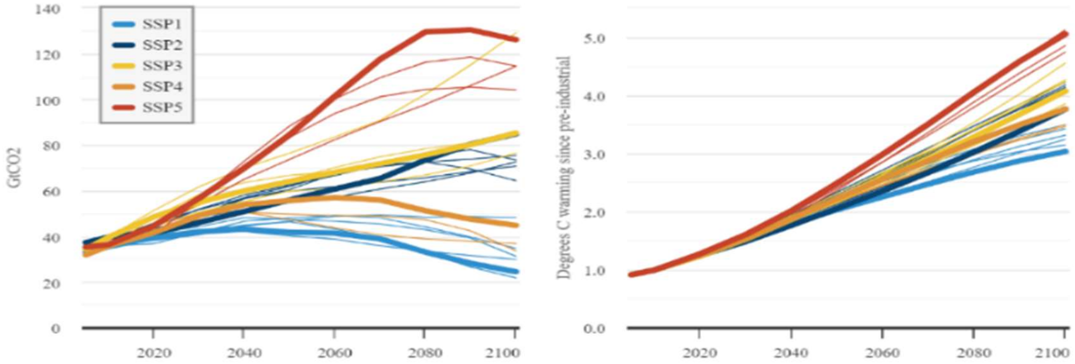

Figure 1. CO2 emissions (left) in gigatons (GtCO2) and global mean surface temperature change relative to pre-industrial levels (right) in Celsius (°C) across all models and SSPs for baseline no-climate-policy scenarios. The primary model for each SSP is shown by a thicker line, while all other models that run for that SSP have thin lines. Image Source: SSP database (O’Neill et al. 2017).

existing CMIP6 weather datasets into future weather files (into .epw format). This is done by using simulated monthly changes from global climate models to adjust present weather data files (Troup and Fannon 2016).

The second method utilized in this study was the Future Weather Generator (FWG), which directly produces .epw files from specific CMIP6 models. While FWG's capacity is limited compared to EPWshiftr, as users cannot freely select SSPs, data periods, or original CMIP6 datasets, it offers the advantage of a more straightforward and faster process.

The third method involves the Future and Extreme Weather Data project, funded by the United States Department of Energy (DOE). Conducted jointly by Argonne National Laboratory, Oak Ridge National Laboratory, and Sandia National Laboratory, this project developed future extreme weather data for use in building design and retrofits (DOE 2023). The data focuses on SSP 5-8.5 and produces future TMY weather files in the .epw format from six different CMIP6 models. This method statistically selects representative months from multiple years and combines them to create a single representative year for a given period, resulting in a Future Typical Meteorological Year (fTMY) (Bass et al. 2022 & Chowdhury et el. 2024). This study downloaded fTMY files from the project's website[4] and used them for this paper's resilience and equity analysis. Table 1 highlights the key attributes selected for analysis from the three methods described above. These three methods utilize different climate models and SSP scenarios. Notably, SSP4-6.0 is excluded from all three methods. Additionally, fTMY data only includes SSP5-8.5.

Table 1. The list of the most important global attributes and climate models chosen for this study to produce future weather files.

Method	EPWshiftr	Future Weather Generator (FWG)	DOE funded project
Climate Model (activity_id)	ScenarioMIP	Ensemble of 6 CMIP6 models	ACCESS-CM2
Experiment_id (SSP)	ssp126, ssp245, ssp370, ssp585	ssp126, ssp245, ssp370, ssp585	ssp585
Years	2020-2080	2050 (2036-2065),2080 (2066-2095)	2020-2039,2040,2059,2060-2079
Frequency	hour	hour	hour
Variable_id (variables)	"tas","tasmax","tasmin", "hurs","psl","rlds","rsds ","sfcWind","clt"	"tas","tasmax","tasmin", "hurs","psl","rlds","rsds ","sfcWind","clt"	"Air Temp", "Longwave", "Shortwave", "Vapor Pressure", "Vapor Pressure Deficit", "Relative Humidity". "Precipitation", "Wind"," Pressure"
Method	Morphing	Morphing	fTMY

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[4] fTMY datasets can be downloaded from the following website: https://zenodo.org/records/10815041.

Building Energy Modeling

This study examines a real-world PHIUS Design Certified AMF building in South Boston, utilizing the energy modeling software 'eQUEST' (Figure 2) based on a 100% construction document progress set. It is important to note that the eQUEST model was not initially used for the Passive House Certification process, as PHIUS mandates using WUFI Passive software for certification. However, eQUEST was selected for this study due to its compatibility with future weather files generated by the three methods previously mentioned.

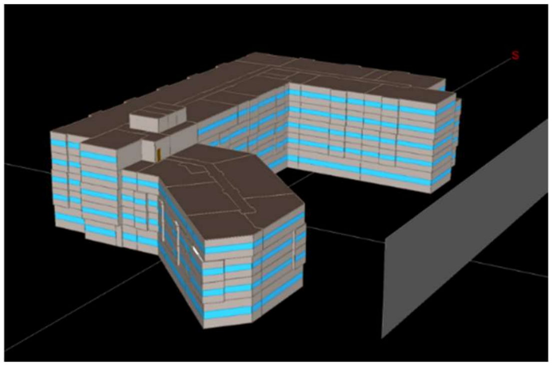


Figure 2. eQUEST Model of the case building

The building spans approximately 125,871 ft² and has a footprint of about 26,000 ft². It is five stories and includes 104 residential units, ranging from one-bedroom to three-bedroom layouts. The residential units are equipped with air-source heat pumps for heating and cooling. The heat pump features heating efficiencies ranging from 8.6 HSPF to 9.4 HSPF and cooling efficiencies ranging from 10.3 EER to 12.5 EER. Ventilation is provided using central rooftop energy recovery ventilators (ERV) with an efficiency of 84%.

Table 2. Four Building Cases and Envelope Assumptions

Building Case	**Case A**	**Case B**	**Case C**	**Case D**
Model Guideline	PHIUS 2021 Standard	ASHRAE 90.1-2019	ASHRAE 90.1-2010	Worst case scenario
Roof	R-40	R-30	R-20	R-3.2
Exterior Wall	R-26	R-18	R-15	R-4
Slab	R-16	R-20 for 24"	R-10 for 24"	No insulation
Window	U-0.17, SHGC-0.39	U-0.35, SHGC-0.38	U-0.35, SHGC-0.4	U-1.04, SHGC-0.86
Airtightness/ Infiltration Rate	0.06 cfm cfm/ft² at 50 pascals	0.3 cfm/ft² at 75 pascals	0.4 cfm/ft² at 75 pascals	0.4 cfm/ft² at 75 pascals

This study examined the influence of climate change on four envelope assembly typologies, with all other variables, such as building geometry and orientation, HVAC, DHW, and other equipment performance, remaining unchanged. As outlined in Table 2, three envelope assemblies were based on energy codes enforced from 2010 to today, and one assembly assumed no insulation to demonstrate the most dramatic scenario. This study performed energy simulations using Cases A, B, C, and D in Table 2, paired with future weather datasets generated from EPWshiftr and FWG, ranging from 2020 to 2080 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Modeling for Resilience

Resilience can be evaluated through various lenses, such as risk avoidance, passive survivability, durability, and longevity (White et al. 2020). Passive survivability is the ability of a building to maintain livable conditions without energy and water. This study focuses on maintaining livable indoor thermal conditions during power outages, which are directly impacted by outdoor temperatures.

Standard Effective Temperature (SET) is the most commonly used metric to estimate survivability under extreme weather (Franconi et al. 2023). However, eQUEST cannot generate the necessary outputs for SET calculations. Therefore, we use the 'acceptable thermal conditions for occupant-controlled naturally conditioned spaces' from ASHRAE 55, which defines livable temperature conditions as between 50°F and 93°F (ASHRAE 2016).

We analyzed hourly dry-bulb temperatures in the TMY3 dataset and selected the coldest three days in January (1/9-1/11) and the hottest three days in July (7/7-7/9) for the resilience study. HVAC and ERV systems were turned off during these periods in eQUEST. During summer power outages, we assumed occupants would open windows 15% of the time for natural ventilation.

This study examined livable conditions by focusing on hourly indoor temperature changes in a two-bedroom unit. Energy simulations for summer and winter power outages were conducted using Cases A, B, C, and D in Table 2, paired with TMY3, fTMY2020-2039, fTMY2040-2059, and fTMY2060-2080 datasets, which represents the worst-case scenario under SSP5-8.5.We then calculated the percentage of hours when indoor temperatures fell outside the ASHRAE acceptable thermal range (50°F to 93°F).

Metrics for Equity

The third focus of this study is equity. This study uses energy burden as an equity metric to discuss the financial impacts of climate change on tenants in our case study units. It is a crucial metric for understanding the financial stress that energy expenses place on households, particularly low-income and marginalized communities. (Drehobl et el. 2020). Energy burden is defined by the following equation:

$$Energy\ Burden = \frac{Utility\ Cost}{Household\ Income}$$

We used electricity rate projections from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (U.S. Energy Information Administration 2023) and simulated energy consumption for Cases A, B, C, and D, paired with TMY3, fTMY2020-2039, fTMY2040-2059, and fTMY2060-2080 datasets, to estimate utility costs from 2020 to 2080 under SSP5-8.5. Since the building is owned by BHA, tenant household income estimates were based on Federal Section 8 low-income brackets from the BHA website, categorizing financial situations into low, very low, and extremely low (BHA 2022). This study does not account for utility allowances and other subsidies, as these are not consistently available to all tenants and are subject to political changes. An annual inflation rate of 2.3% was assumed to adjust future household income ranges when calculating the energy burden.

Discussion and Result Analysis

Future Weather Data

This study employs three methods to obtain future weather data for building energy simulation: Scenario-MIP data morphed using ‘EPWshiftr’, data from FWG, and fTMY data from a DOE-funded study. The primary goal is to illustrate that, while all methods indicate a warming trend, they exhibit notable differences, as depicted in Figure 3, which presents the daily mean temperature for the year 2050, showcasing the trends from each dataset along with their mean trendlines. Additionally, the methods vary in accessibility. The ‘EPWshiftr’ approach is the most complex, requiring technical knowledge of CMIP6 file structures and the tool itself. Conversely, FWG and fTMY data are more user-friendly but have limitations regarding year selection and climate models.

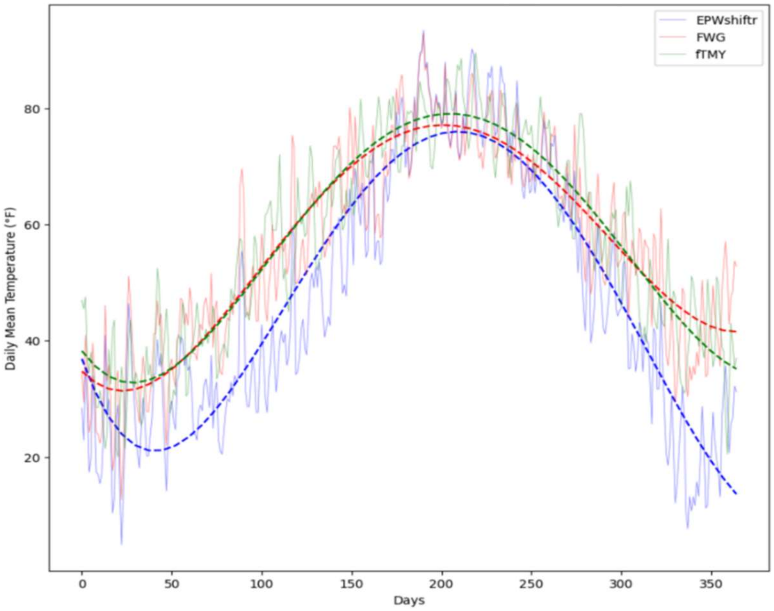


Figure 3. Comparing the future weather data from CMIP6 Scenario-MIP (morphed using EPWshiftr), FWG and fTMY for 2050.

Therefore, when selecting future climate datasets, it is important to carefully consider the source of the data depending on the goal of this study. It must be noted that the simulated data for future weather is not to be taken as accurate predictions. Rather, the different datasets tuned to different initial conditions and parametric settings should be regarded as a range of possible future scenarios by which we should evaluate our current understanding of the trend in climate change and its related consequences.

Impact of Future Weather Files on Building Energy Performance

Figure 4 illustrates the EUI of our case building projected for 2080. The analysis of simulation results indicates that models using EPWshiftr data exhibit higher EUI values compared to those using FWG data due to colder winter conditions, as depicted in Figure 3. For example, in Case C, the EUI using EPWshiftr data is 75 kBtu/ft², which is a 25% increase over the 60 kBtu/ft² obtained with FWG data. The overall building energy usage is more influenced by the weather generation methods (EPWshiftr vs FWG) than by the different SSPs. EUI values remain relatively consistent across various SSP scenarios when using FWG-generated weather files. In contrast, EPWshiftr weather files show that envelope insulation and airtightness significantly impact EUI, especially under SSP1-2.6, the best-case scenario among the four SSPs. Surprisingly, Case C using EPWshiftr SSP1-2.6 weather files exhibits higher EUI than those using SSP5-8.5 weather files, which is the worst-case scenario.

Further examination of cases under EPWshiftr reveals that Case A demonstrates lower sensitivity to different SSPs. On the other hand, buildings with reduced insulation, such as in Case C, show greater sensitivity to varying SSPs.

Figure 5 compares the combined energy consumption for heating and cooling across different climate change scenarios. The primary impact of climate change is the increase in temperatures, which significantly affects heating and cooling energy consumption in the simulations. Notably, Case C under SSP1-2.6 consumes 470,000 kWh, which is the highest of all other SSP cases.

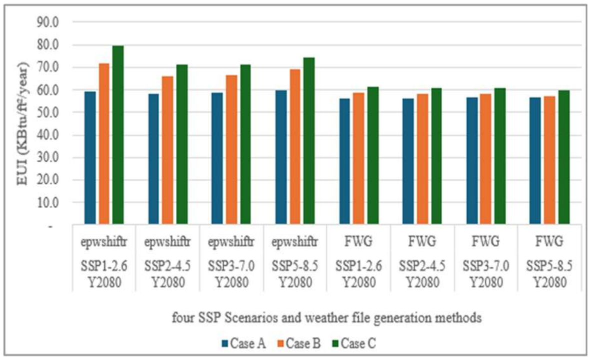


Figure 4. Energy Use Intensity across four SSP scenarios and weather file generation methods

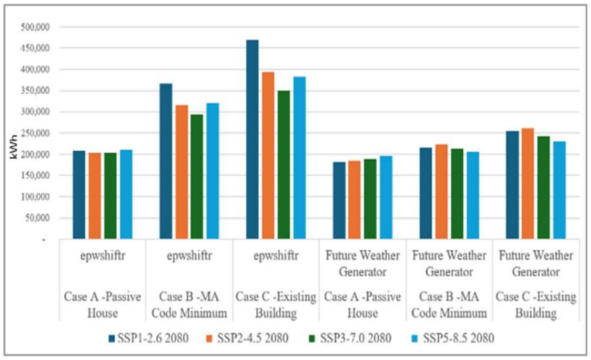


Figure 5. Heating and Cooling Usage in 2080

To explain why the most favorable climate change scenario (SSP1-2.6) resulted in the poorest energy performance, a closer examination of end-uses is required, including heating, heat pump supplemental heating, and cooling. Figure 6 visually depicts the distribution of each end-use. The passive House envelope (Case A) primarily relies on cooling, making it less susceptible to rising temperatures in winter than in summer. Conversely, Case C, featuring an ASHRAE 90.1-2010 envelope with less insulation and a higher infiltration rate than Case A, exhibits greater sensitivity to colder winter temperatures. SSP1-2.6, characterized by colder winters compared to SSP2-4.5, 3-7.0, and 5-8.5, increased heat pump operation to maintain indoor setpoints. In addition, under the SSP1-2.6 weather, the frequency of supplemental electric heater activation is higher than in other SSPs, ultimately resulting in higher energy consumption for heating.

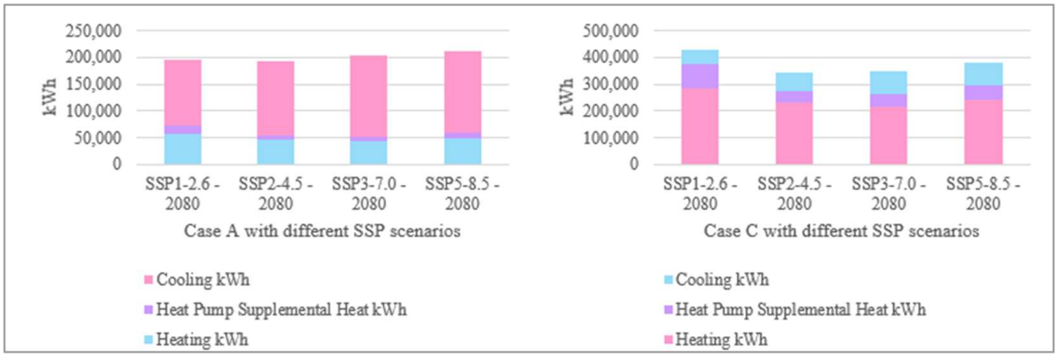


Figure 6. Heating, Heat Pump Supplemental Heat, and cooling between Case A and C – EPWshiftr file in the year 2080

Table 3 presents the trend of decreasing heating energy usage and increasing cooling energy usage over the years under SSP5-8.5, using EPWshiftr weather files. The changes are not linear, likely due to uncertainties in projected weather datasets (ScenarioMIP from CMIP6). Zooming out and comparing simulation results from 2020 to 2080, a noticeable trend emerges: cooling energy usage rises yearly while heating energy usage decreases. The decrease in heating energy usage is similar across Cases A, B, and C, with a reduction of about 10% in 2025 and 30% in 2075. In contrast, the Passive House envelope (Case A) is more resistant to increases in cooling energy usage, showing a 17% increase by 2080. Cases B and C, however, exhibit a 40% increase in cooling energy usage over the same period.

Table 3. Percentage Change of Heating and Cooling Energy under SSP5-8.5

Year of the Morphed Weather File (EPWshiftr, SSP5-8.5)		2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080
Heating Energy Use	Case A - Passive House Envelope	-	-8%	-12%	-21%	-10%	-12%	-19%	-29%	-16%	-34%	-19%	-32%	-24%
	Case B - ASHRAE 90.1-2019 Envelope	-	-10%	-12%	-21%	-10%	-12%	-17%	-28%	-14%	-30%	-18%	-30%	-23%
	Case C - ASHRAE 90.1-2010 Envelope	-	-9%	-11%	-22%	-10%	-13%	-17%	-28%	-14%	-31%	-19%	-31%	-24%
Cooling Energy Use	Case A - Passive House Envelope	-	1%	-3%	7%	0%	6%	4%	11%	8%	14%	9%	14%	17%
	Case B - ASHRAE 90.1-2019 Envelope	-	1%	-8%	11%	-4%	10%	7%	18%	20%	27%	20%	25%	39%
	Case C - ASHRAE 90.1-2010 Envelope	-	1%	-8%	11%	-3%	10%	6%	18%	19%	26%	20%	26%	40%

Figure 7 and Figure 8 depict the responses of Cases A and C to climate change over time under the worst-case scenario SSP5-8.5 respectively.

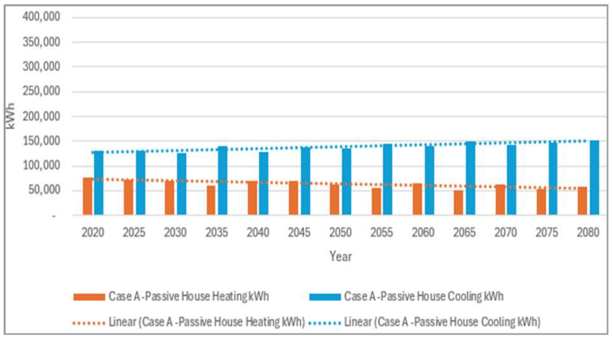


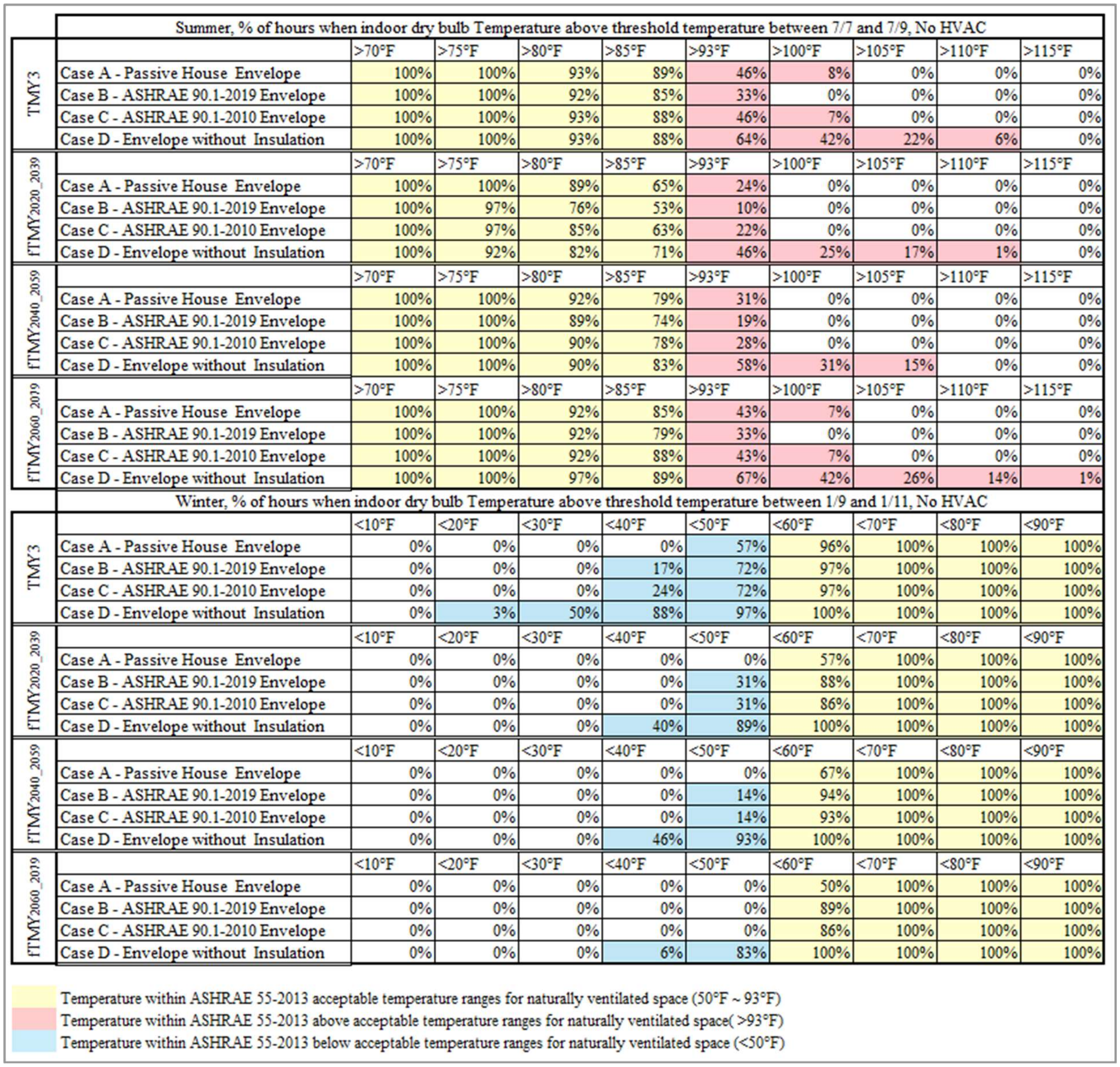
Figure 7. SSP5-8.5 Case A – Heating & Cooling Energy Use

Figure 8. SSP5-8.5 Case C – Heating & Cooling Energy Use

Impact of Climate Change on Resilience

Table 4 highlights the percentage of hours when indoor temperatures exceed the ASHRAE 55 acceptable thermal thresholds (50°F to 93°F). Cells are yellow if temperatures are within the acceptable range, red if above 93°F, and blue if below 50°F.

Table 4. Percentage of hours when indoor temperature is outside of ASHRAE acceptable range



Summer, % of hours when indoor dry bulb Temperature above threshold temperature between 7/7 and 7/9, No HVAC

		>70°F	>75°F	>80°F	>85°F	>93°F	>100°F	>105°F	>110°F	>115°F
TMY3	Case A - Passive House Envelope	100%	100%	93%	89%	46%	8%	0%	0%	0%
	Case B - ASHRAE 90.1-2019 Envelope	100%	100%	92%	85%	33%	0%	0%	0%	0%
	Case C - ASHRAE 90.1-2010 Envelope	100%	100%	93%	88%	46%	7%	0%	0%	0%
	Case D - Envelope without Insulation	100%	100%	93%	88%	64%	42%	22%	6%	0%
fTMY2020_2039		>70°F	>75°F	>80°F	>85°F	>93°F	>100°F	>105°F	>110°F	>115°F
	Case A - Passive House Envelope	100%	100%	89%	65%	24%	0%	0%	0%	0%
	Case B - ASHRAE 90.1-2019 Envelope	100%	97%	76%	53%	10%	0%	0%	0%	0%
	Case C - ASHRAE 90.1-2010 Envelope	100%	97%	85%	63%	22%	0%	0%	0%	0%
	Case D - Envelope without Insulation	100%	92%	82%	71%	46%	25%	17%	1%	0%
fTMY2040_2059		>70°F	>75°F	>80°F	>85°F	>93°F	>100°F	>105°F	>110°F	>115°F
	Case A - Passive House Envelope	100%	100%	92%	79%	31%	0%	0%	0%	0%
	Case B - ASHRAE 90.1-2019 Envelope	100%	100%	89%	74%	19%	0%	0%	0%	0%
	Case C - ASHRAE 90.1-2010 Envelope	100%	100%	90%	78%	28%	0%	0%	0%	0%
	Case D - Envelope without Insulation	100%	100%	90%	83%	58%	31%	15%	0%	0%
fTMY2060_2019		>70°F	>75°F	>80°F	>85°F	>93°F	>100°F	>105°F	>110°F	>115°F
	Case A - Passive House Envelope	100%	100%	92%	85%	43%	7%	0%	0%	0%
	Case B - ASHRAE 90.1-2019 Envelope	100%	100%	92%	79%	33%	0%	0%	0%	0%
	Case C - ASHRAE 90.1-2010 Envelope	100%	100%	92%	88%	43%	7%	0%	0%	0%
	Case D - Envelope without Insulation	100%	100%	97%	89%	67%	42%	26%	14%	1%

Winter, % of hours when indoor dry bulb Temperature above threshold temperature between 1/9 and 1/11, No HVAC

		<10°F	<20°F	<30°F	<40°F	<50°F	<60°F	<70°F	<80°F	<90°F
TMY3	Case A - Passive House Envelope	0%	0%	0%	0%	57%	96%	100%	100%	100%
	Case B - ASHRAE 90.1-2019 Envelope	0%	0%	0%	17%	72%	97%	100%	100%	100%
	Case C - ASHRAE 90.1-2010 Envelope	0%	0%	0%	24%	72%	97%	100%	100%	100%
	Case D - Envelope without Insulation	0%	3%	50%	88%	97%	100%	100%	100%	100%
fTMY2020_2039		<10°F	<20°F	<30°F	<40°F	<50°F	<60°F	<70°F	<80°F	<90°F
	Case A - Passive House Envelope	0%	0%	0%	0%	0%	57%	100%	100%	100%
	Case B - ASHRAE 90.1-2019 Envelope	0%	0%	0%	0%	31%	88%	100%	100%	100%
	Case C - ASHRAE 90.1-2010 Envelope	0%	0%	0%	0%	31%	86%	100%	100%	100%
	Case D - Envelope without Insulation	0%	0%	0%	40%	89%	100%	100%	100%	100%
fTMY2040_2059		<10°F	<20°F	<30°F	<40°F	<50°F	<60°F	<70°F	<80°F	<90°F
	Case A - Passive House Envelope	0%	0%	0%	0%	0%	67%	100%	100%	100%
	Case B - ASHRAE 90.1-2019 Envelope	0%	0%	0%	0%	14%	94%	100%	100%	100%
	Case C - ASHRAE 90.1-2010 Envelope	0%	0%	0%	0%	14%	93%	100%	100%	100%
	Case D - Envelope without Insulation	0%	0%	0%	46%	93%	100%	100%	100%	100%
fTMY2060_2019		<10°F	<20°F	<30°F	<40°F	<50°F	<60°F	<70°F	<80°F	<90°F
	Case A - Passive House Envelope	0%	0%	0%	0%	0%	50%	100%	100%	100%
	Case B - ASHRAE 90.1-2019 Envelope	0%	0%	0%	0%	0%	89%	100%	100%	100%
	Case C - ASHRAE 90.1-2010 Envelope	0%	0%	0%	0%	0%	86%	100%	100%	100%
	Case D - Envelope without Insulation	0%	0%	0%	6%	83%	100%	100%	100%	100%

🟨 Temperature within ASHRAE 55-2013 acceptable temperature ranges for naturally ventilated space (50°F ~ 93°F)
🟥 Temperature within ASHRAE 55-2013 above acceptable temperature ranges for naturally ventilated space(>93°F)
🟦 Temperature within ASHRAE 55-2013 below acceptable temperature ranges for naturally ventilated space (<50°F)

Case B represents the case AMF at the current MA Stretch energy code, with an envelope that meets ASHRAE 90.1-2019 performance requirement for climate zone 5A. Case B shows the best thermal resilience in summer, with only 10% of hours above 93°F between 2020 and 2039, compared to around 22% for Cases A and C. Even between 2060 and 2079, as the temperature rises due to climate change, Case B only has 33% of hours above the acceptable temperature threshold, while Case A has 67% and Case C has 43%. However, in winter, Case B only performs similarly to Case C, with comparable percentages of hours below 50°F.

Due to its high insulation and low infiltration rate, Case A has the best thermal resilience in winter, with 0% of hours below 50°F from 2020 to 2079. Comparatively, However, Case A does not perform as well in summer, showing similar percentages of indoor temperatures as Case C. These results indicate that the Passive House envelope excels in winter but not summer. Conversely, like Case B, moderate insulation and infiltration envelopes perform best in hot summer conditions.

Due to its lack of insulation, Case D performs the worst in terms of thermal resilience. In summer, Case D has the highest percentage of hours above acceptable thermal conditions, reaching indoor temperatures over 115°F in fTMY 2060-2079. Case D performs similarly poorly in winter, with 83% of hours below acceptable conditions using fTMY2060-2079 and 97% using TMY3. Buildings without insulation are the least resilient thermally, as heat can easily penetrate the envelope.

Over time, from 2020 to 2079, indoor temperatures during summer outages increase, while during winter outages decrease. For instance, in Case B, the percentage of hours above 93°F increases from 10% to 33%. In winter, the percentage of hours below 50°F decreases from 31% to 0%. These results suggest that indoor temperatures rise over time as climate change increases ambient temperatures.

Figure 9 shows indoor temperatures in Cases A, B, and C remain mostly below 93°F, except around noon. In these cases, indoor temperatures rise on the second and third days. The peak indoor temperature in Case B during power outages is nearly identical to the outdoor temperature, while Cases A and C are about 6°F higher. Figure 10 presents a similar temperature distribution. For Cases A, B, and C, models using the fTMY2040-2059 weather file have fewer hours above 93°F compared to the TMY3 weather file.

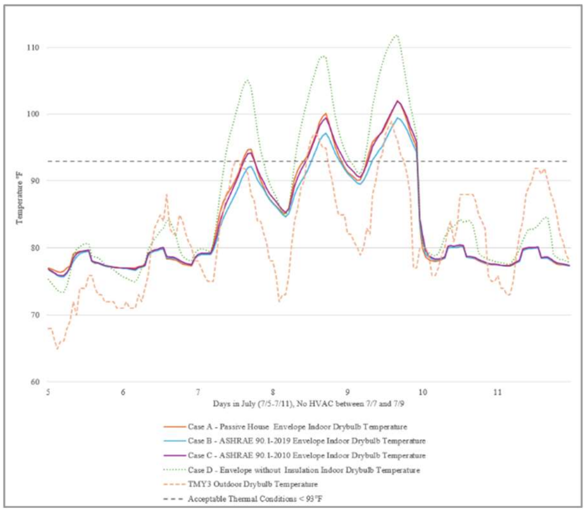


Figure 9. Summer indoor dry-bulb temperature. Simulation with Boston TMY3 weather file.

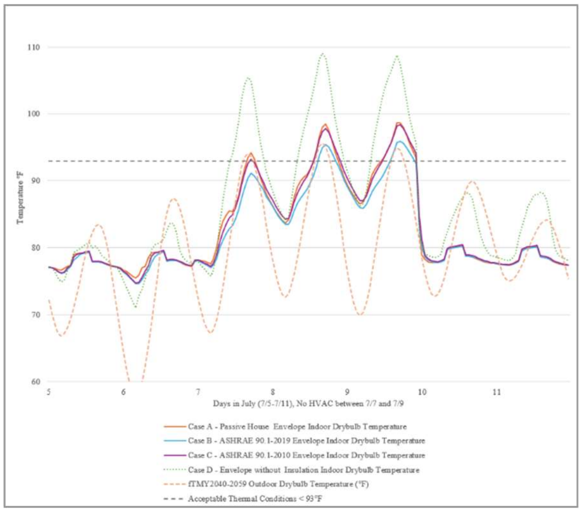


Figure 10. Summer indoor dry-bulb temperature. Simulation with Suffolk fTMY 2040-2060.

Figure 11 and Figure 12 demonstrate how envelope insulation enhances resilience during winter outages. Passive House construction (Case A) has the highest R-value and is the most resilient to temperature increases during power outages. In Case A, the hourly indoor temperature decreased slowly over three days compared to other cases.

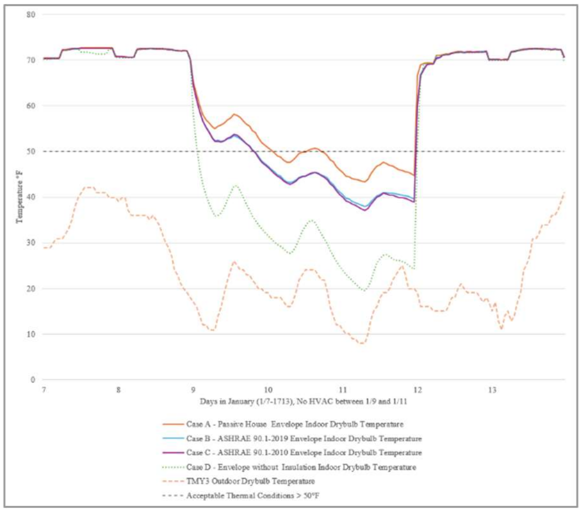


Figure 11. Winter indoor dry-bulb temperature. Simulation with Boston TMY3 weather file.

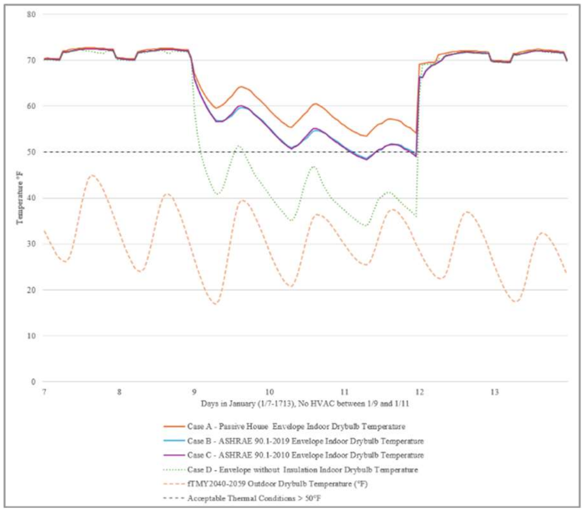


Figure 12. Winter indoor dry-bulb temperature. Simulation with Suffolk fTMY 2040-2060.

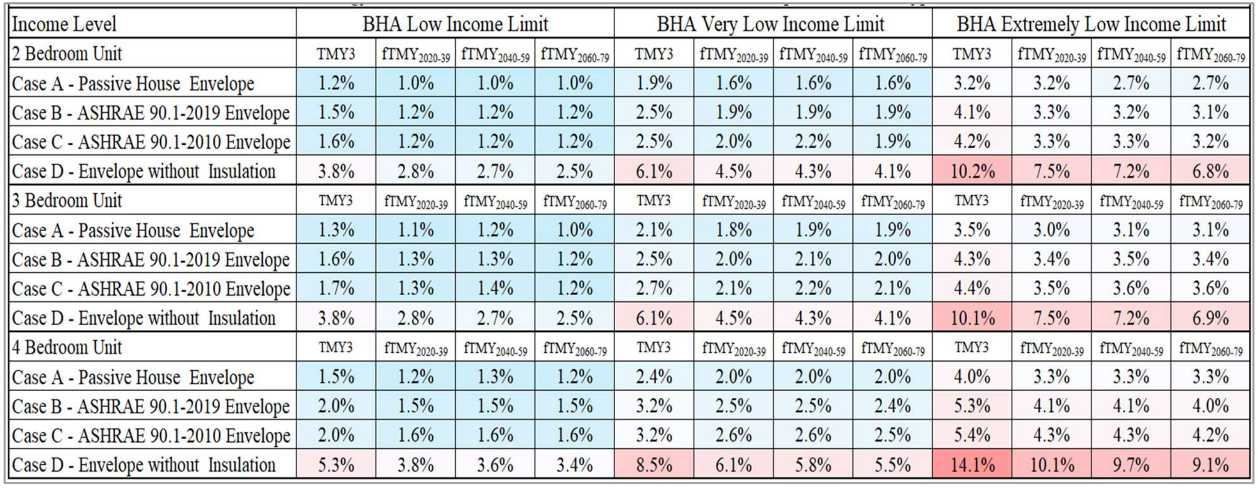
Impact of Climate Change on Equity

Table 5 illustrates the impact of climate change on the energy burden experienced by families across three different income brackets. The figure also delineates the energy burden for tenants renting various housing units, specifically two-bedroom, three-bedroom, and four-bedroom units. According to the American Council for an Energy-Efficient Economy (ACEEE), an energy burden exceeding 6% is classified as severe (Drehobl et al., 2020).

The results indicate that tenants in lower income brackets may experience a higher energy burden if they live in poorly insulated buildings, such as in Case D. For instance, tenants residing in Case A three-bedroom units under fTMY 2020-2039 face an energy burden of 3%. However, this burden increases substantially to 7.5% for those living in Case D units.

Moreover, the findings suggest that climate change may reduce the energy burden as temperatures rise over time, particularly for units in Case D. Conversely, the impact of climate change on energy burden is relatively smaller for units in Case A. This is attributed to the Passive House envelope and lower energy usage of Case A units, making them more resilient to the changing climate.

Table 5. Energy Burden under different weather files and envelope construction types



Income Level	BHA Low Income Limit				BHA Very Low Income Limit				BHA Extremely Low Income Limit			
2 Bedroom Unit	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$
Case A - Passive House Envelope	1.2%	1.0%	1.0%	1.0%	1.9%	1.6%	1.6%	1.6%	3.2%	3.2%	2.7%	2.7%
Case B - ASHRAE 90.1-2019 Envelope	1.5%	1.2%	1.2%	1.2%	2.5%	1.9%	1.9%	1.9%	4.1%	3.3%	3.2%	3.1%
Case C - ASHRAE 90.1-2010 Envelope	1.6%	1.2%	1.2%	1.2%	2.5%	2.0%	2.2%	1.9%	4.2%	3.3%	3.3%	3.2%
Case D - Envelope without Insulation	3.8%	2.8%	2.7%	2.5%	6.1%	4.5%	4.3%	4.1%	10.2%	7.5%	7.2%	6.8%
3 Bedroom Unit	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$
Case A - Passive House Envelope	1.3%	1.1%	1.2%	1.0%	2.1%	1.8%	1.9%	1.9%	3.5%	3.0%	3.1%	3.1%
Case B - ASHRAE 90.1-2019 Envelope	1.6%	1.3%	1.3%	1.2%	2.5%	2.0%	2.1%	2.0%	4.3%	3.4%	3.5%	3.4%
Case C - ASHRAE 90.1-2010 Envelope	1.7%	1.3%	1.4%	1.2%	2.7%	2.1%	2.2%	2.1%	4.4%	3.5%	3.6%	3.6%
Case D - Envelope without Insulation	3.8%	2.8%	2.7%	2.5%	6.1%	4.5%	4.3%	4.1%	10.1%	7.5%	7.2%	6.9%
4 Bedroom Unit	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$	TMY3	$fTMY_{2020-39}$	$fTMY_{2040-59}$	$fTMY_{2060-79}$
Case A - Passive House Envelope	1.5%	1.2%	1.3%	1.2%	2.4%	2.0%	2.0%	2.0%	4.0%	3.3%	3.3%	3.3%
Case B - ASHRAE 90.1-2019 Envelope	2.0%	1.5%	1.5%	1.5%	3.2%	2.5%	2.5%	2.4%	5.3%	4.1%	4.1%	4.0%
Case C - ASHRAE 90.1-2010 Envelope	2.0%	1.6%	1.6%	1.6%	3.2%	2.6%	2.6%	2.5%	5.4%	4.3%	4.3%	4.2%
Case D - Envelope without Insulation	5.3%	3.8%	3.6%	3.4%	8.5%	6.1%	5.8%	5.5%	14.1%	10.1%	9.7%	9.1%

Conclusion

Weather and climate are highly complex phenomena, making precise long-term predictions challenging even with advanced computers. However, simulations can provide a range of results critical for decision-making, and these simulations should include evaluating the impact of future weather. Despite differences in specific yearly predictions, all datasets consistently indicate the overall trend of climate change. Nevertheless, it is still important to consider which CMIP6 dataset to choose from for energy modeling as they can lead to noticeable variations in the simulated results.

The process of acquiring future weather data and converting it into a format compatible with energy modeling software when using EPWshiftr and FWG is complicated. However, the DOE-funded study that produced various fTMY files as standard weather files significantly reduces the complexity and can be adopted by engineers and designers to streamline their simulations.

This study examined the energy performance, resilience, and equity of case buildings in Boston with varying envelope designs and airtightness levels under future climate scenarios. Simulation results highlight the primary impact of climate change on heating and cooling energy usage. Despite this, the overall energy consumption of the case AMF remains relatively unaffected, as heating and cooling account for only 15% to 25% of total energy usage.

Our analysis shows that Passive House buildings (Case A) will be the most resilient during power outages on the coldest days due to their significant insulation in the envelopes under current and future climates. Other code-compliant buildings (Cases B and C) are less resilient than Passive House under TMY3 weather conditions, with the majority of hours outside the ASHRAE acceptable range. However, as temperatures rise in the future, Cases B and C will become more resilient as most of their indoor temperatures will remain within ASHRAE acceptable ranges even after three days of power outages.

Under the current and future climate change scenarios, Case A is not the most resilient compared to Cases B and C. In some weather scenarios, Case A is the least resilient among the three. This result points to a challenge for Passive House envelopes when dealing with extreme heat during power outages.

Regarding equity, for low-income communities living in well-insulated buildings, the correlation between energy burden and climate change is insignificant. However, for those residing in poorly insulated housing, the energy burden decreases as the climate warms.

This study primarily focuses on the impacts of climate change on building envelope construction types, which is only a small part of a larger narrative. As we face climate urgency, many more aspects of resilience and equity require further research. For instance, climate change may also impact carbon emissions, air quality, humidity, precipitation, flooding, and health. Further investigation into these areas will provide a more comprehensive understanding of the challenges and solutions needed. Incorporating future weather files for building energy studies and design processes can be one step toward meeting these challenges.

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