

Modelling and Analysis of Retrofit Strategies for Mid-Rise Multi-Unit Residential Buildings in  
Toronto: Advancing Energy Efficiency, Comfort, Resilience, and Decarbonization

by

Alexis Minniti

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## **Author's Declaration**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Abstract

Over the past century, global temperatures have risen significantly due to human activity, contributing to more frequent and intense extreme weather events such as heatwaves. This underscores the urgent need to reduce emissions from the building sector while enhancing the climate resilience of existing buildings. Most of the buildings that will be in use in Canada by 2050 have already been constructed; therefore, the existing building stock must be retrofitted to enhance energy efficiency and increase occupant safety and comfort under extreme future climate conditions.

The objective of this study is to evaluate the effectiveness of various energy conservation measures (ECMs) in advancing energy efficiency and decarbonization, while enhancing thermal resilience and reducing thermal stress, for mid-rise multi-unit residential buildings (MURBs) in Toronto. The ECMs evaluated in this study included the effective thermal resistances (R-values) of the wall assembly and the roof assembly, window thermal conductance (U-factor), infiltration, roof colour, lighting power density (LPD), equipment power density (EPD) and domestic hot water (DHW) peak flow rate. Mechanical system upgrades, including the addition of cooling and ventilation, as well as the electrification of space heating and DHW, were also studied.

A numerical archetype building energy model was calibrated with actual energy consumption data from an existing MURB. This baseline model was then used to (1) develop a surrogate model for predicting energy use intensity (EUI) and (2) to evaluate the effectiveness of the ECMs under current and future climate conditions. A Multilayer Perceptron (MLP, a feedforward neural network) and fourth-degree polynomial surrogate model achieved coefficient of determination ( $R^2$ ) values of at least 99.98% and 99.82% respectively, and normalized root mean squared errors (NRMSE) of at most 0.17% and 0.55%, respectively. The polynomial equations can easily be used to predict the EUI of similar MURBs for a variety of ECMs.

The numerical and surrogate models were then used to evaluate the impact of various ECMs on reducing EUI, advancing building decarbonization and improving occupant thermal comfort. The building envelope ECMs were successful at reducing the EUI, and adding cooling and ventilation maintained safe and comfortable indoor conditions throughout the year. Electrification was an effective method for reducing operational carbon emissions due to Ontario's low carbon electricity grid. The combination of envelope retrofits and mechanical

system upgrades resulted in a 57% reduction in EUI (from 270 kWh/m<sup>2</sup>/year to 116 kWh/m<sup>2</sup>/year), a 90% reduction in operational carbon emissions (from 43 kg CO<sub>2</sub>e/m<sup>2</sup>/yr to 4 kg CO<sub>2</sub>e/m<sup>2</sup>/yr), maintained comfortable conditions for 97% of the year (8,481 out of 8760 hours of the year), and maintained safe conditions for all hours of the year. Under predicted future climate conditions, EUI was lower due to the lower heating demand; however, the thermal resilience metrics decreased by up to 47% highlighting the need to consider both energy efficiency and thermal resilience when retrofitting MURBs.

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## **List of Abbreviations**

AMY: Average Meteorological Year

ANSI: American National Standards Institute

ASHRAE: American Society of Heating, Refrigerating and Air Conditioning Engineers

BPS: Building Performance Simulation

CAGBC: Canadian Green Building Council

CDD: Cooling Degree Day

CEDI: Cooling Energy Demand Intensity

CMHC: Canadian Mortgage and Housing Corporation

CVRMSE: Coefficient Of Variation of the Root Mean Squared Error

CWEC: Canadian Weather Year for Energy Calculation

DHW: Domestic Hot Water

DOE: Department Of Energy

ECM: Energy Conservation Measure

EPD: Equipment Power Density

EPW: EnergyPlus Weather

ERV: Energy Recovery Ventilator

ERWH: Electric-Resistance Water Heaters

EUI: Energy Use Intensity

GHG: Greenhouse Gas

GSAT: Global Surface Air Temperature

GWP: Global Warming Potential

HDD: Heating Degree Day

HPWH: Heat Pump Water Heater

HRC: Heat-Reflective Coating

HVAC: Heating Ventilation Air Conditioning

IDF: Input Data File

KPI: Key Performance Indicators

LBFGS: Limited-Memory Broyden-Goldfarb-Shanno

LCA: Life Cycle Analysis

LHS: Latin Hypercube Sampling

LPD: Lighting Power Density

MAE: Mean Absolute Error

MBE: Mean Bias Error

MLP: Multi-Layer Perceptron

MM: Missing Middle

MURBs: Multi-Unit Residential Building

NECB: National Energy Code for Buildings

NMBE: Normalized Mean Bias Error

NRCan: Natural Resources Canada

NRMSE: Normalized Root Mean Squared Error

NZS: Net Zero Strategy

PCM: Phase Change Material

PNNL: Pacific Northwest National Laboratory

pp: Percentage Point

PS: Passive Survivability

PV: Photovoltaic

RMSE: Root Mean Squared Error

$R^2$ : Coefficient of Determination

SET: Standard Effective Temperature

SHGC: Solar Heat Gain Coefficient

TA: Thermal Autonomy

TEDI: Thermal Energy Demand Intensity

TMY: Typical Meteorological Year

VIP: Vacuum Insulated Panels

WWR: Window-To-Wall Ratio

# **1 Introduction**

This chapter provides background information on the importance of retrofitting existing buildings in the Canadian housing market, the objectives of this study, and the scope of work undertaken.

## **1.1 Background**

Buildings account for 18% of greenhouse gas emissions in Canada [1] and there is a significant opportunity for decarbonization of the built environment. To mitigate climate change, Canada has committed to reducing its emissions by 40% to 45% below 2005 levels by 2030 and to reaching net-zero emissions by 2050 [2]. Over 50% of the buildings that will be in use by 2050 have already been built [3]; therefore, deep energy retrofits are crucial for Canada's decarbonization strategy. It has been projected that for Canada to reach net-zero emissions by 2050, 600,000 homes and 32,000,000 m<sup>2</sup> of commercial property will need to be retrofitted annually until 2040 [4]. Additionally, to achieve Canada's net-zero emission goals, the country will become more reliant on electricity, with projections for non-emitting electricity to account for as much as 55% of final energy demand in 2050 [5].

Significant global warming has occurred over the last century due to anthropogenic emissions, as the average global surface air temperature (GSAT) from 2011 to 2020 is 1.1°C higher than that of pre-industrial times (1850 to 1900). The average GSAT from 2021 to 2040 is projected to increase to 1.5°C above that of pre-industrial times [6]. Canada is experiencing warming at nearly twice the global rate [7], and nine of the ten warmest years on record have occurred during the last 25 years [8]. The continued increase in temperature leads to an increase in the frequency and severity of extreme weather events. Environment and Climate Change Canada attributed the June 2024 heat wave in central and eastern Canada to climate change [9]. Extreme heat was identified as the leading cause of illness and death from weather-related hazards in Canada [10]. Existing buildings must be retrofitted to maintain safe and comfortable conditions for occupants under current and future climate conditions.

## **1.2 Objectives**

This research aims to evaluate the effectiveness of various energy conservation measures (ECMs) in achieving energy efficiency and decarbonization, while enhancing thermal resilience

and reducing thermal stress, for mid-rise multi-unit residential buildings (MURBs) in Toronto. The three objectives are summarized below.

1. To support stakeholder (i.e., property owners, municipalities, and policy makers) decision-making by developing an easy-to-use, data-driven model that estimates the energy use intensity (EUI) of mid-rise MURBs under different ECM scenarios.
2. Quantify the trade-offs between EUI reduction and thermal resilience by evaluating how various ECMs affect both energy performance and indoor thermal stress metrics.
3. Assess the long-term effectiveness of retrofit strategies by analyzing their performance under future climate scenarios using key performance indicators (KPIs).

### **1.3 Scope**

This study is specific to existing mid-rise MURBs in the City of Toronto, Ontario, Canada (climate zone 5A according to ASHRAE [11]). The ECMs studied cover envelope and mechanical system upgrades. The envelope upgrades include improved wall and roof insulation, reduced infiltration, and replacement of windows. The mechanical system upgrades are represented by three scenarios: business-as-usual (i.e., natural gas for both space heating and domestic hot water), partial electrification (i.e., natural gas for domestic hot water and auxiliary space heating), and full electrification. The study also assesses the impact of reduced plug and lighting loads, as well as lower domestic hot water (DHW) flow rates.

It should be noted that no specific product types or manufacturers are referenced; only their performance metrics are provided, which reflect the available building materials, systems, and practices in the Canadian market.

The effectiveness of the different ECMs is assessed for both current (through 2023) and projected future climate conditions using a high-emissions scenario (Representative Concentration Pathway 8.5) that projects at least a 3.5 °C increase in Ontario's annual mean temperature by 2080, relative to the 1991–2021 baseline [12] [13]. This study does not include any life cycle analysis or cost analysis for the upgrade measures.

To demonstrate the impact of various ECMs, this study uses an existing mid-rise MURB as a reference case. The energy model is calibrated using monthly utility bill data specific to this

building. As a result, the energy model is confirmed to model monthly energy performance accurately, but it is not calibrated to reflect daily or hourly dynamics. As such, it should not be used in applications where short-term energy profiles are critical, such as demand-side management or load-shifting analyses.

## **2 Literature Review**

This section presents a review of previous studies to reinforce the motivation for this research and to inform the decisions made in this study. Insights from their methods and results guided the selection of ECMs and KPIs for this study.

### **2.1 Housing Crisis**

Canada's national housing crisis presents one of its greatest social and economic challenges. The lack of housing stock and the growing population are straining housing affordability in large urban centers, small towns, and northern and rural communities [14]. The population of the City of Toronto in 2022 was 3,025,647, and the population density was 4,803 people per square kilometre [15]. Toronto's population increased by 2.3% from 2016 to 2021, and an additional 168,300 proposed units were approved during this period, representing the potential for continued growth [16].

The Canadian Mortgage and Housing Corporation (CMHC) reported that in 2004, an Ontario household with an average income would have had to spend 40% of its household income on housing, while in 2021, the average Canadian household spent almost 60% of its income on housing. The province of Ontario aims to reduce housing costs to 37% of the average household income [17]. Canada needs to increase its housing supply to support its growing population while maintaining affordability.

### **2.2 Mid-Rise MURBs & Missing Middle as a Solution**

Mid-rise MURBs and missing middle (MM) housing are two residential archetypes that are well-suited to address both climate change and the housing crisis.

The City of Toronto classifies mid-rise buildings as those that are no taller than the width of the adjacent street. In Toronto, streets are between 16.5 and 45 metres wide, meaning that buildings can be classified as mid-rise if they are between 5 and 14 storeys. Mid-rise buildings are designed to integrate within established neighbourhoods, are transit-supportive, and often include either commercial or retail space on the ground floor [18]. Mid-rise MURBs offer high housing density without the high carbon footprint associated with high-rises due to shallower foundations and reduced concrete and steel usage [19]. Another benefit of mid-rise MURBs is that they have a larger roof surface area relative to their total conditioned floor area compared to high-rise

MURBs. This potentially provides enough space for the installation of rooftop photovoltaics to offset a significant portion of the buildings' electricity demand [20].

Another important building typology for addressing the housing crisis is MM housing. Architect Daniel Parolek, who developed the term 'missing middle', described it as *“a range of multi-unit or clustered housing types that are in scale with single-family homes that help meet the growing demand for walkable urban living.”* MM housing can serve as a transitional step to mid-rise MURBs, as implementing more MM housing can help ease zoning restrictions and shift public perception in favour of MURBs [21]. This will enable urban areas to gradually densify, eventually scaling up to mid-rise MURBs with zero-carbon performance goals.

Both new construction and the continued use of the existing stock of mid-rise MURBs and MM housing provide a solution to Canada's housing crisis.

### **2.3 Addressing Emission Targets Through Retrofits**

A critical step in addressing the Canadian housing crisis is maintaining and retrofitting the existing housing stock. The CMHC estimated the Canadian housing stock to be 16.53 million household units in 2022 [22]. They projected that the housing stock will be 18.19 million units by 2030, indicating that the majority of Canada's future housing stock will consist of buildings that exist today. Additionally, they predicted that to restore affordability, 3.45 million additional units would be required.

Natural Resources Canada's (NRCan) Canada Green Building Strategy highlights the importance of ensuring that Canada's existing buildings can withstand the impacts of climate change, including extreme weather events such as floods, wildfires, and hurricanes, as well as changes in temperature and precipitation [23]. Additionally, to reach Canada's goal of net-zero emissions from the building sector by 2050, the retrofit rate of the existing housing stock must increase to at least 3% per year. The Canada Green Building Council (CAGBC) estimates that retrofits of large buildings can reduce emissions by 51% or 21.2 million tonnes by 2030 [24].

Retrofits offer a significant opportunity for reducing carbon emissions when considering the life cycle of a building. Hasik et al. [25] compared whole-building life cycle assessments (LCAs) for a renovation case study in Philadelphia, Pennsylvania, and a hypothetical new construction scenario. They used the Tool for the Reduction and Assessment of Chemical and Other

Environmental Impacts (version 2.1) impact assessment method to calculate the environmental impacts in both case studies, including acidification potential, eutrophication potential, global warming potential, ozone depletion potential, smog formation potential, and non-renewable energy demand [26]. Across the categories assessed, the renovation scenario reduced impacts by 53 to 75% when compared to the new construction scenario. This was primarily due to the concrete, masonry, and metals introduced in the new construction, which are absent in the renovation scenario and have high global warming potentials (GWP).

Similarly, Leichter et al. [27] reviewed case studies of LCAs of renovation and reconstruction scenarios from around the world to determine which is preferable when considering GWP. They reviewed 44 records, of which 72% focused on residential buildings (28% focused on multi-family housing, 21% focused on single-family housing, and the remainder included both). Of the 68% of conclusive studies, 45% recommended the renovation scenario, and 18% recommended the reconstruction scenario. Renovation was preferred due to its lower embodied GHG emissions (environmental), lower investment and lifecycle costs (economic), and preservation of cultural heritage and community (social). It also highlights the environmental benefits of adaptive reuse and renovation over new construction, particularly in terms of GWP and overall resource consumption.

McGrath et al. [28] also performed an LCA to compare the environmental performance of a PassivHaus retrofit [29] with that of a new build constructed to current Irish standards. The retrofit case involved a 3-storey Victorian house, and the new build was a semi-detached block of two houses that achieved a B2 Building Energy Rating, which is considered a strong result indicative of good energy efficiency. They found that in both cases, the reduction in operational carbon emissions due to the retrofits far outweighed the increase in embodied carbon emissions during the assembly and end-of-life stages. They recommended deep energy retrofits to reduce operational carbon emissions significantly. During deep energy retrofits, many building components remain unchanged (i.e., structural components), which helps avoid embodied carbon emissions that would otherwise be generated in a new construction scenario. The carbon pay-back period of the retrofit was found to be only four years.

While previous studies have focused on colder climates, similar conclusions were also found in a hot-arid climate. Belpoliti et al. [30] investigated the case study of the Mohammed Bin Rashid

Housing Establishment headquarters in the United Arab Emirates by performing a comparative analysis of retrofit versus new construction. They compared both approaches in terms of energy performance, feasibility, and functionality. Both scenarios were designed to achieve the same functionality and achieved similar energy performance targets. The embodied carbon was not considered in this comparison; however, they acknowledged that the retrofit scenario would have lower embodied carbon emissions. The cost of the proposed retrofit was found to be 31% less than the cost of new construction.

Overall, retrofitting existing buildings is a critical and cost-effective strategy to address Canada's housing crisis, reduce emissions in the building sector, and enhance climate resilience, offering significant environmental and economic advantages over new construction.

## **2.4 Existing Incentives and Policies**

To address the housing crisis, many governing bodies have implemented plans and policies that encourage the use of mid-rise MURBs and MM housing as a solution. The government of Ontario passed the More Homes Built Faster Act in 2022 in support of Ontario's Housing Supply Action Plan [31]. This legislation addresses the importance of MM building forms by strengthening the framework for additional residential units. The act also highlights the need to revitalize the aging rental housing stock to improve energy efficiency. In further efforts to preserve the existing building stock, municipalities can enact bylaws to prevent the demolition of multi-unit residential properties of six units or more. For new construction, bureaucratic processes will be streamlined, and the Planning Act will be modified to move toward "as-of-right" zoning, reducing project approval timelines and accelerating construction. The More Homes Built Faster Act also has an initiative to promote sustainable building practices through changes to the building code, which would allow municipalities to require green standards.

In addition to Ontario's policies, the City of Toronto has a climate action strategy to achieve net-zero GHG emissions by 2040 called the TransformTO Net Zero Strategy (NZS) [32]. In the NZS, buildings are identified as one of the key sectors emitting GHG emissions. In addition to reducing GHG emissions, the NZS also focuses on enhancing climate resilience. The NZS recommends annual emission performance reporting and public disclosure for all existing buildings. It also aims to support building retrofit initiatives by streamlining permitting and approval processes for deep retrofits and providing additional financing options. Toronto's NZS

supports improvements to the building envelope and a shift from fossil fuel heating systems to electric heating systems, such as heat pumps. The City of Toronto has four retrofit financing programs for home and building owners with the goal of identifying and implementing low-carbon retrofits [33]. These programs are the Home Energy Loan Program, Energy Retrofit Loan Program, High-Rise Retrofit Improvement Support Program, and Taking Action on Tower Renewal. Each program has different eligibility requirements, but they all promote decarbonization and energy efficiency measures. There are also external retrofit funding programs supported by organizations such as Enbridge Gas and the CMHC [34].

The City of Toronto requires housing that accommodates a wide range of household sizes and lifestyles. In recent years, there has been a growing focus on constructing high-rise residential buildings in densely populated areas; however, a notable lack of small-scale apartment buildings remains. Constructing more mid-rise MURBs would align with the City of Toronto's Official Plan [35] as they allow for increased density at the boundaries of neighbourhoods along transportation corridors and transit routes. This is a component of Toronto's 2022 to 2026 Housing Action Plan, which aims to increase the supply of housing within complete, inclusive, and sustainable communities with critical infrastructure to support growth [36].

Similarly, the City of Vancouver is facing a housing affordability crisis and the need to accommodate significant population growth. The city has developed the Broadway Plan, which aims to integrate housing, jobs, and amenities along the new Broadway subway line [37]. Mid-rise MURBs comprise a significant portion of the housing in this area, and they are particularly desirable for this project, as many are mixed-use, providing both housing and employment opportunities. The Broadway Plan will guide the preparation and review of rezoning and development permit applications and inform potential updates to the Zoning and Development Bylaw.

While Canada has begun implementing policies and incentives to support mid-rise MURBs and deep retrofits, it remains behind other countries with comparable environmental targets. Existing efforts are important first steps; however, more aggressive and coordinated action is needed, particularly in removing regulatory barriers, such as restrictive city by-laws, that limit MURB development in major urban centres.

## 2.5 Characterizing the Existing Mid-Rise MURB Stock

An important first step when studying MURB retrofits is to characterize the existing MURB stock. In 2018, NRCan surveyed MURB energy consumption, and of the 11,715 MURBs in Canada surveyed, 28.9% were constructed between 1970 and 1979, representing the largest share of all MURB vintages [38]. Furthermore, MURBs built from 1970 to 1979 account for 31.5 % of the energy consumption for all MURBs surveyed, higher than all the other vintages.

In 2022, apartments accounted for 29.8% of Ontario's housing stock [39] and the largest share of apartment vintages was from 1961 to 1977 (18.8%) [40]. NRCan's Comprehensive Energy Use Database for the Residential Sector breaks down energy use and GHG emissions by end use for apartment buildings in Ontario in 2022 [41]. The breakdown of energy use by end use is shown in Figure 2.1 and the breakdown of GHG emissions by end use is shown in Figure 2.2.

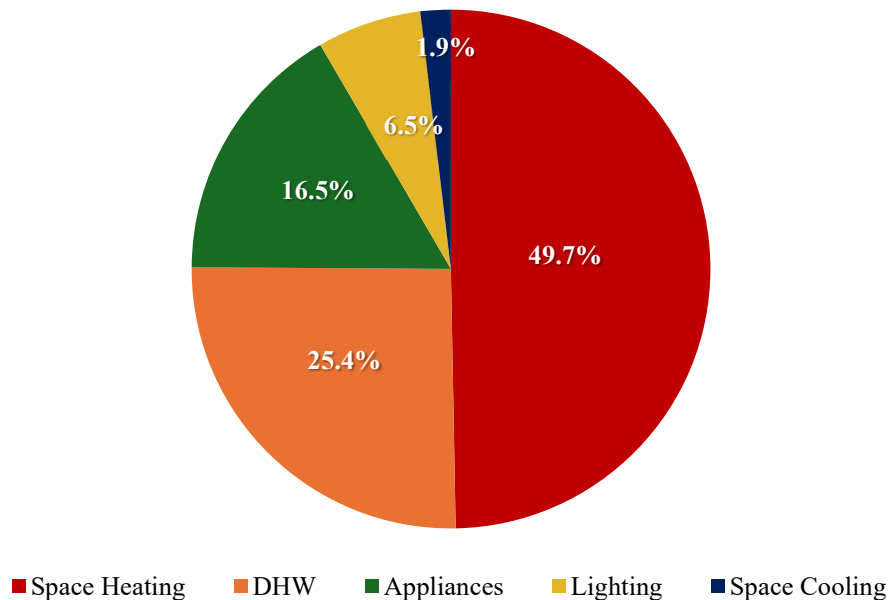


**Figure 2.1: Energy Use Breakdown by End Use**

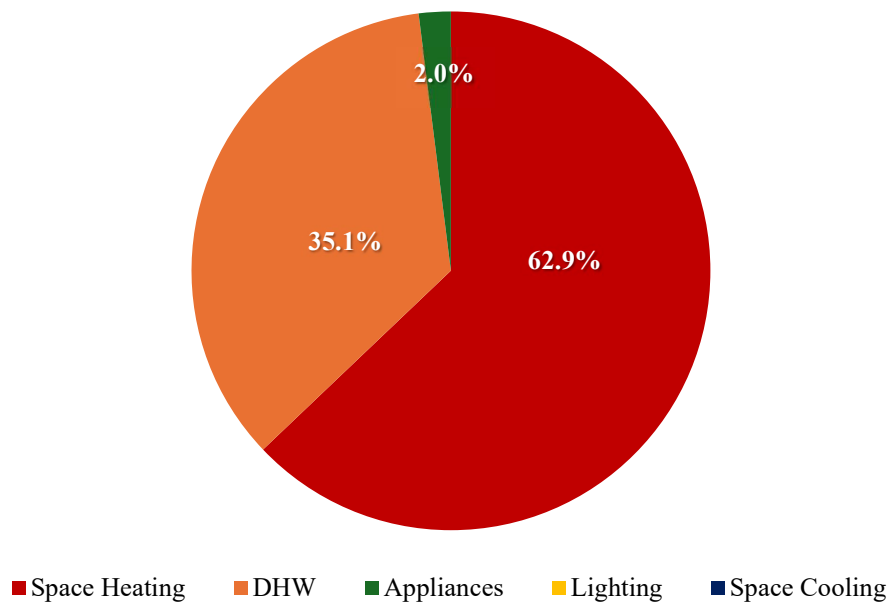


**Figure 2.2: GHG Emissions Breakdown by End Use**

The CAGBC also studied mid-rise MURBs from the 1970s across Canada and developed representative archetypes for major Canadian cities [24]. The Toronto archetype was a 13-storey MURB with a window-to-wall ratio (WWR) of 30% and a floor area of 13,000 m<sup>2</sup>. The building envelope consisted of exposed concrete walls with interior insulation, non-thermally broken balconies, and double-glazed windows. The mechanical systems included 80% efficient gas-fired constant volume make-up air units, hydronic baseboard convectors connected to an 80% efficient gas-fired boiler, an 80% efficient central gas-fired water heater, and half of the units used window-installed air conditioning units. The EUI for this archetype was 64 kWh/m<sup>2</sup>/yr for electricity and 246 kWh/m<sup>2</sup>/yr for natural gas, resulting in a total EUI of 310 kWh/m<sup>2</sup>/yr. The GHG intensity was 1 kg CO<sub>2</sub>e/m<sup>2</sup>/yr for electricity and 43 kg CO<sub>2</sub>e/m<sup>2</sup>/yr for natural gas, resulting in a total GHG intensity of 44 kg CO<sub>2</sub>e/m<sup>2</sup>/yr.

Furthermore, Touchie et al. [42] attempted to identify MURB typologies with the highest EUI in Toronto, as they would be the best candidates for deep energy retrofit projects. The study was unable to establish energy use trends based on building characteristics, such as gross floor area, number of suites, or building height. A wide range of energy intensities was observed for Toronto MURBs; however, a trend observed was that they have significantly higher natural gas intensities than electricity intensities, as shown in Figure 2.3. It was found that the average EUI

decreased from older MURBs to newer MURBs until the 1970s, primarily due to the introduction of newer, more efficient mechanical systems. A slight increase in the average EUI of MURBs occurred from the 1970s to the 1990s due to increased WWRs in MURBs. The WWR and the boiler efficiency (for space heating) were the building characteristics with the strongest correlations to energy use. Touchie et al. speculated that if the buildings with the highest energy intensities underwent relatively inexpensive adjustments to building operations and maintenance, they would be able to achieve the median energy intensity. This has the potential to reduce the absolute energy consumption of Toronto's MURB stock by more than 10%.

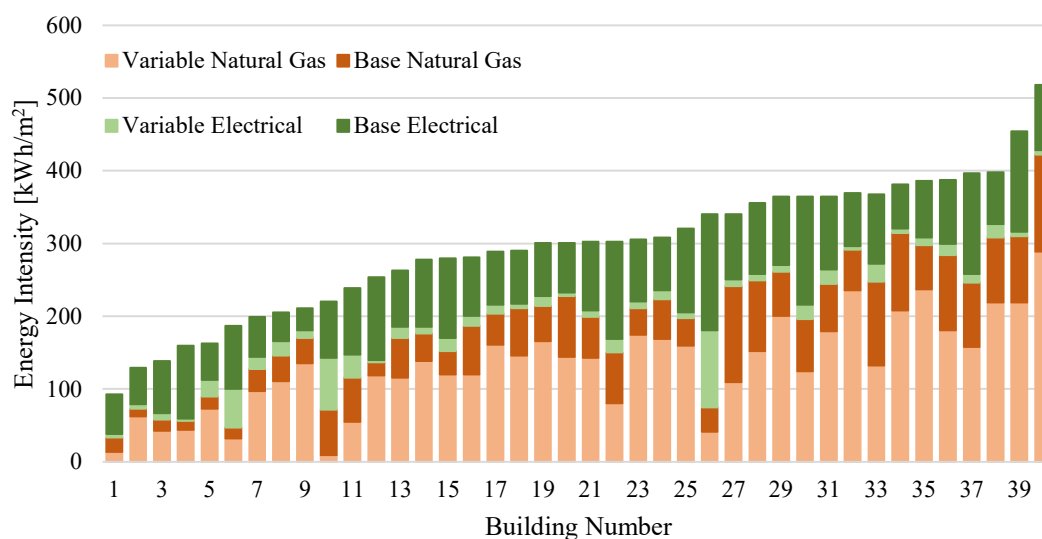


**Figure 2.3 Total Annual Energy Intensity**

Similarly, Ghajarkhosravi et al. [43] assessed performance indicators for evaluating the energy consumption of buildings in Toronto. They studied 120 MURBs and concluded that the best benchmarks to help the government and building owners make effective decisions on improving their buildings' efficiency and carbon footprint are: energy consumption per floor surface area, per number of occupants, per number of units, and per number of floors. Four benchmarking methods were used, one of which was a model-based approach. In this approach, buildings were modelled in a building energy simulation program, and benchmarking was performed. A crucial consideration for this approach was ensuring that the simulation model's results accurately reflect the actual consumption data, which was achieved through a model calibration process.

Additionally, to make comparisons between buildings regardless of factors such as size, the performance indicators were normalized by floor area. They also found that natural gas had a

higher contribution (74%) to the total energy consumption compared to electricity. Space heating accounted for 53% of total energy consumption, while base loads, primarily water heating, accounted for 21%. Most of the electricity consumption was attributed to base loads (lighting and household equipment).

Toronto's aging MURB stock presents a significant opportunity for energy retrofits and decarbonization. The most prevalent MURB vintage is from the 1970s, and this vintage also accounts for a significant portion of MURB energy consumption. The majority of MURB energy consumption is attributed to heating; therefore, retrofit projects should target reducing space conditioning loads.

## **2.6 Previous Studies on MURB Retrofits**

Numerous studies have investigated the impacts of MURB retrofits. Most relevant are those that have investigated how MURB retrofits have impacted energy consumption, carbon emissions, thermal comfort, and thermal resilience.

### **2.6.1 Energy Consumption and Carbon Emissions**

Many building retrofit studies focused on the impacts of retrofit measures on energy consumption and carbon emissions. Taileb et al. [44] analyzed two MURBs located in Toronto using data from a three-year energy audit and building energy simulations in e-Quest [45]. Monthly energy consumption data for the MURBs was extracted from gas and electricity bills and used to create a baseline model that reflects the actual consumption. This baseline model was then used to simulate various retrofit scenarios, including improvements to the window glazing units and improvements to the insulation. Improving the windows from single-glazed, clear windows to triple-glazed windows with two low-e coatings resulted in a 38% reduction in natural gas consumption. Increasing the wall insulation from RSI-1.4 (R-8) to RSI-3.70 (R-21) achieved a 4% reduction in natural gas consumption; however, there were no discernible energy savings when the roof insulation was upgraded from RSI-4.4 (R-25) to RSI-7.4 (R-42).

Similarly, Touchie et al. [46] assessed the potential of various energy retrofits for MURBs in the Greater Toronto Area. An analysis of four MURBs was performed using calibrated energy models to determine the impact of various retrofit measures on EUI. It was found that upgrades to airtightness, envelope insulation, and boiler efficiency were the most effective retrofits for reducing EUI. The existing MURBs had airtightness values ranging from 0.65 to 2.00 L/(s·m<sup>2</sup>),

envelope insulation thicknesses ranging from 25 to 75 mm of polystyrene, and boiler efficiencies ranging from 60% to 85%. The retrofit MURBs had airtightness values ranging from 0.25 to 1.50 L/(s·m<sup>2</sup>), envelope insulation thicknesses ranging from 50 to 100 mm of polystyrene, and boiler efficiencies ranging from 65% to 95%. When the most effective retrofit measure (either an airtightness, envelope insulation, or boiler efficiency upgrade) was applied to each of the four MURBs, the average reduction in GHG emissions was 16%.

Beyond Canada, Ghazwani et al. [47] conducted a literature review on the effectiveness, performance, economic and environmental impacts, retrofitting techniques, and challenges of using advanced building envelope materials for energy retrofits in residential buildings across various climates. The study focused on relatively novel and advanced envelope technologies, including phase change materials (PCMs), aerogels, vacuum insulation panels (VIPs), and heat-reflective coatings (HRCs), which are not yet widely adopted in conventional retrofitting practice. In this study, 68 documents (55 peer-reviewed articles and 13 conference papers) were evaluated, and the findings included that PCMs improve occupant comfort and cooling system efficiency, aerogel insulation effectively reduces heat transfer, VIPs have superior insulation performance when properly installed, and HRCs reduce cooling loads but may increase heating loads. Implementing these materials results in a 38.74% reduction in GHG emissions. While they require a substantial upfront investment, long-term energy savings typically offset the initial costs.

Focusing on equipment, Ilanthodi et al. [48] compared the carbon emissions of three different water heating technologies: electric-resistance water heaters (ERWH), heat pump water heaters (HPWH), and gas-fired boilers. Historical hot water demand data was used from sample buildings that feature centralized gas-fired boilers with continuous sensor data measuring water flow rates, temperatures, boiler firing rates, and water consumption rates. Using this data, they computed the carbon emissions of all the water heater types at an equivalent level of service. It was found that HPWHs had the lowest emissions, and gas-fired boilers generated 1.80 to 2.02 times more emissions than HPWHs due to combustion. ERWHs generated 3.76 to 4.08 times more emissions than HPWHs due to their relative inefficiency.

Finally, Cheung et al. [49] investigated passive retrofits to reduce the cooling requirement of a high-rise apartment building in Hong Kong. This study was performed using energy simulations

run in TRNSYS [50]. The base model used in this study was modelled after an existing building and was verified by comparing the average annual cooling energy required for the simulation with published survey data, which showed a deviation of less than 8%. The retrofits studied included adding EPS insulation to the external walls (25, 50, 75, 100 mm), changing the colour of the external walls (reducing solar absorptance), upgrading the glazing units, adding external shading (up to 1.5 m depth), and combinations of these measures. Adding 100 mm of EPS to the external walls resulted in a 19.4% reduction in cooling energy (29.2% reduction in peak cooling load). A 30% reduction of solar absorptance of the external walls resulted in a 12.6% reduction in cooling energy. Replacing the existing glazing with a single layer of 6 mm glass with a reflective coating resulted in a 4.6% reduction in cooling energy (a 5.4% reduction in peak cooling load). Adding external shading reduced the cooling load, but the benefits decreased as the shading was extended beyond 500 mm. The combined retrofit of 100 mm EPS exterior wall insulation, white coloured walls (solar absorptance of 0.2), replacing the glazing with 6 mm glass with a reflective coating, and adding 1.5 m external shading resulted in a 31.4% reduction in cooling energy and a 36.8% reduction in the peak cooling load.

These studies have illustrated the effects several passive retrofit measures, including improved airtightness, increased insulation, and window upgrades, have on energy efficiency. They also demonstrated the benefits of these passive measures, as well as the electrification of heating, ventilation, and air conditioning (HVAC) systems, for reducing the operational emissions of MURBs. However, it is also crucial to understand how these retrofits impact the thermal comfort and thermal resilience of MURBs.

### **2.6.2 Thermal Comfort Evaluation**

Occupant thermal comfort is a crucial consideration when evaluating a building's performance. Andargie et al. [51] shared that the factors affecting occupant thermal comfort in MURBs are temperature and humidity, clothing, and air speed. In MURBs, temperature and humidity are influenced by access to operable windows (which varies due to safety concerns), access to thermostat controls, portable heaters or fans, and high WWRs. High WWRs can increase discomfort by causing excessive solar gains during the cooling season and leading to low mean radiant temperatures and cold drafts during the heating season.

Retrofit projects commonly prioritize reducing energy consumption and carbon emissions; however, it is also crucial to evaluate how these retrofits will impact thermal comfort. Vakalis et al. [52] investigated opportunities to improve occupant thermal comfort while performing retrofits primarily focused on decarbonization. This study focused on retrofits to HVAC systems (boiler and air handler unit replacements) in seven social housing MURBs. Thermal comfort was assessed by monitoring the temperature and relative humidity and classifying whether the conditions were in a comfortable range according to the Graphic Comfort Zone Method from section 5.31 of American National Standards Institute (ANSI)/American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 [53]. Retrofits targeting decarbonization had both positive and negative effects on thermal comfort; however, in all cases, thermal comfort ratings changed by no more than 10% between pre- and post-retrofit conditions. Similarly, Perera et al. [54] investigated the impact of building energy efficiency and advanced green building design concepts on indoor environmental quality, specifically thermal comfort and indoor air circulation. They developed a baseline MURB model based on minimum envelope requirements outlined in the National Energy Code for Buildings (NECB) [55] for Climate Zone 5. Then they applied several ECMs, including exterior wall insulation, double-glazed low-e windows, and a reduced WWR, to enhance energy efficiency. They monitored the indoor temperature distribution and evaluated thermal comfort following ASHRAE 55 [53]. They focused on five parameters: indoor air temperature, operative temperature, occupant clothing, relative humidity, and metabolic rate. The ECMs resulted in a 20% reduction in site energy. Overall, the ECMs improved thermal comfort conditions according to all three ASHRAE 55 calculation methods (simple static graph, Fanger, and adaptive).

There is no clear conclusion on how energy efficiency and decarbonization retrofits impact occupant thermal comfort. In some studies, thermal comfort was improved, while in others, the retrofits had a minimal impact on thermal comfort. Additionally, the methods that are used to assess thermal comfort vary between studies.

### **2.6.3 Thermal Resilience**

With the increasing frequency and intensity of extreme weather events, it is crucial to design buildings that promote safe indoor conditions for occupants. Sheng et al. [56] used building performance simulations (BPS) to assess the thermal resilience of an assisted living facility in

Houston, Texas, during power outages coinciding with extreme weather events. The metrics selected to assess thermal resilience were the standard effective temperature (SET) degree-hours, the heat index, and the hours of safety. SET considers the following parameters: indoor air dry-bulb temperature, relative humidity, mean surface radiant temperature, air velocity, occupant activity level, and occupant clothing level. The heat index considers both relative humidity and air temperature to measure the human-perceived equivalent temperature. The hours of safety measures the amount of time a building can maintain safe conditions above the set temperature threshold during a cold event. The weather data used were for two extreme weather events, drawn from 30 years of historical weather data. The following passive upgrades were applied to the building envelope to determine their impact on thermal resilience: exterior wall and roof insulation, a cool coating on the walls and roof, interior window shades, solar film on windows, air sealing, and opening the windows for natural ventilation. The thermal resilience of the assisted living facility was evaluated for power outage scenarios with and without backup power, considering extreme hot and cold weather conditions. Most of the passive envelope upgrades enhanced thermal resilience in both hot and cold events; however, air tightness compromised thermal resilience during the heatwave. Natural ventilation was identified as an important measure for mitigating overheating in the summer.

Siu et al. [57] also investigated the use of BPS to evaluate thermal resilience. The metrics identified in this study were broken into two groups: metrics of thermal stress and metrics of thermal resilience. Thermal stress occurs when an indoor space reaches a critical level of discomfort or hazard. Thermal resilience refers to a building's ability to extend the period of safe occupancy and its capacity to restore the indoor environment to a habitable state. The metrics used to evaluate thermal stress include dry-bulb temperature, operative temperature, wet-bulb temperature, heat index, and discomfort index. The metrics used to evaluate thermal resilience include time to critical level, maximum level of thermal stress, and time of exceedance. Another important consideration is the weather file data that is used for running thermal resilience simulations. Typically, historical weather data is used; however, as more extreme conditions are expected in the future, predictions of future weather data should also be considered.

Green-Mignacca et al. [58] investigated thermal resilience under extreme weather conditions through their analysis of two upgrade scenarios for a mid-rise MURB archetype in three

locations across Canada (Vancouver, Ottawa, and Charlottetown). The first upgrade scenario was compliant with the 2020 NECB, and the other upgrade scenario was a high-performance option. The building was simulated in EnergyPlus [59], and the hourly indoor zone temperatures were used in the resiliency analysis. The heating and cooling setpoints were 20°C and 25°C, respectively, and the simulation was run starting four weeks prior to a power outage event until two days afterward. To create the weather event files, three types of weather files were utilized: Average Meteorological Year (AMY), Typical Meteorological Year (TMY), and Canadian Weather Year for Energy Calculation (CWEC). The dry bulb temperature and relative humidity were copied from the AMY to the TMY, and then the TMY was formatted to match the CWEC. The archetype building used was the Department of Energy (DOE) mid-rise apartment building archetype model [60]. The upgrades considered in this study were the wall RSI (4.16 to 4.8 m<sup>2</sup>·K/W), roof RSI (7.24 to 13.2 m<sup>2</sup>·K/W), the infiltration rate (reduction of 70% to 90% of existing building's infiltration rate), the photovoltaic (PV) efficiency (15% or 24% efficiency) and battery storage size (160, 480 and 800 kWh storage size). Reducing infiltration and increasing wall and roof RSI improved the thermal resilience during cold weather events, but harmed resilience during hot weather events (note that no natural ventilation strategies were evaluated). The improvement in thermal resilience during the cold weather far outweighed the negative impacts during the hot weather.

Rostami et al. [61] employed a similar methodology in their work to develop a risk metric that assesses thermal and incidental risks in buildings during power outages. They evaluated the thermal decay of two buildings in London, Ontario, during an ice storm and a heat wave. One building was a code-minimum design (reference building), and the other was the as-built final design. This study utilized AMY weather data and referenced historical extreme weather events that resulted in power outages. To model the extreme weather events and power outages in EnergyPlus [59], the simulation period was shortened to start four weeks before the event and end two days after. The scenario was simulated twice, with and without a power outage. They found that PV generation was sufficient to maintain safe indoor temperatures during the heat wave but was insufficient during the ice storm. Their results also reinforced that adding insulation and reducing infiltration (with ventilation) improved resilience.

Focusing on extreme heat events, Siu et al. [62] researched the current and future roles of Canadian building codes in protecting occupants from overheating. The 2025 National Building Code is currently under development, and provisions addressing overheating have been proposed [63]. The first proposed strategy for reducing overheating was to limit the solar heat gain coefficient (SHGC) of windows and doors based on the climate zone and the WWR. The second strategy was mandating the installation of active cooling systems if the calculated or simulated interior temperature exceeds 26°C, the peak cooling load exceeds the minimum peak cooling load (to be determined), or if the location has a 2.5% outdoor air-cooling design temperature higher than a set threshold (to be determined). External shading and natural ventilation should also be investigated as passive solutions that would be effective when active cooling is not operational, due to power outages or equipment failure. Active cooling was found to be effective for reducing overheating; however, it also increased peak cooling load and building energy consumption. Passive measures were not sufficient on their own to prevent overheating; however, they were effective in reducing cooling energy usage, cooling equipment size, and giving occupants control to manage overheating according to weather conditions.

Bartko et al. [64] also investigated the effects of passive cooling measures on overheating in MURBs using EnergyPlus. Several passive cooling measures were studied, including shading, ventilation, glazing type, and thermal mass. In this study, the transient standard effective temperature index was used as a heat stress index. The simulated models were based on NRCan building archetypes. The simulations were run in Ottawa using both historic and future climate data. Infiltration values of 6.86, 5.34, 2.32, and 1.63 ACH at 50 Pa were considered for old, retrofit, current, and future construction, respectively. The models could not be calibrated according to ASHRAE 14 and instead were compared to energy data from NRCan. The results of this study showed that when outdoor temperatures were lower than indoor temperatures, increased natural ventilation was the most effective method for reducing overheating.

Similarly, Ozkan et al. [65] examined how different passive measures impact thermal resilience in MURBs. They examined suites in both Toronto and Vancouver and monitored thermal autonomy (TA) and passive survivability (PS). For the TA analysis, the building was simulated for an entire year with HVAC, lighting, and equipment turned off, and the number of hours when the operative temperature was between 18°C and 25°C was monitored. For the PS analysis, the

active systems were turned off during periods of extreme summer and winter weather, and the amount of time it took for the operative temperature to fall out of the range of 15°C to 30°C after the active systems were shut off was monitored. Parametric building energy simulations were performed with different WWRs (40% to 80%), wall RSIs (4.0, 4.8, 5.6 m<sup>2</sup>·K/W), and glazing U-values (2.5, 1.7, 1.0 W/m<sup>2</sup>·K) to create 11 cases. In the Toronto climate zone, it was found that a high-performance enclosure (wall RSI of 5.6 m<sup>2</sup>·K/W, window U-value of 1.00 W/m<sup>2</sup>·K, and SHGC of 0.25) with operable shading and natural ventilation delivered the best thermal autonomy and passive survivability results.

While a variety of simulation scenarios and performance metrics have been proposed to evaluate building thermal resilience, there is currently no universally accepted method that captures key dimensions such as event frequency, intensity, duration, seasonal timing, and spatial or occupant-related vulnerabilities. For example, in the case of a blackout, it remains unclear whether simulations should assume outages during the hottest and coldest days, how long they should last, or how these disruptions are sequenced within the model. This reflects an active and evolving area of research, with growing interest in developing standardized, comprehensive approaches to resilience assessment.

## **2.7 Impact of Future Climate Conditions**

A crucial consideration when evaluating the effectiveness of ECMs is their performance under future climate conditions. Liyanage et al. [66] examined the process for planning building retrofits and proposed modifications to ensure that these retrofits are effective for future climates. For the pre-retrofit stage, this study proposed performing building audits based on calibrated energy simulations under future climate conditions, rather than using historical performance data, and including KPIs for climate resiliency. During the retrofit design stage, this study recommended incorporating future weather data into BPS and optimizing retrofits to increase longevity. In the retrofit implementation stage, it was recommended to include passive retrofits that will be effective during extreme climate events with power outages. Finally, for the post-retrofit stage, it was recommended to closely monitor performance under extreme conditions, as these are expected to become more frequent in the future.

Similarly, Bagherzadeh et al. [67] studied how ECMs will be impacted by future climate conditions. BPS in EnergyPlus was used to assess the impact of various future climate scenarios

(+1°C, +1.5°C, +2°C, +2.5°C, +3°C, and +3.5°C, along with the current climate for comparison) on two office buildings modelled in multiple locations across Canada (Toronto, Ottawa, and Montreal). The ASHRAE 90.1–2019 prototypical large office model [60] was used as a baseline. Climate zones 5 and 6 were selected because they experience extreme temperature swings, representing a 50°C to 60°C difference between the hottest and coldest days. Three levels of ECMs were selected based on currently available materials and current practices. These retrofits included improvements to the wall insulation, roof insulation, and glazing units. They were applied individually and in combination to determine the effects of individual retrofits and to determine the best overall performing retrofit package. The total heating and cooling energy of the retrofit models was compared to the baseline model to determine their effectiveness, and thermal comfort was estimated through unmet hours. The thermal comfort heating setpoint ranged from 15.6°C during unoccupied periods to 21.0°C during occupied periods, and the cooling setpoint ranged from 24.0°C to 26.7°C. The study found that glazing upgrades significantly reduced heating loads but also increased cooling loads, especially in climate zone 5A. The combination of wall and roof insulation improvements was effective at reducing cooling loads. Annual heating loads were expected to decrease while cooling loads were expected to increase under future climate conditions; therefore, upgrades that reduce cooling loads should be prioritized. The study also identified that the retrofitted buildings had a high sensitivity to climate change as energy use increased by up to 18% for cooling and decreased by up to 41% for heating under future climate conditions.

Baba et al. [68] investigated further how buildings designed for cold climates in Canada experience higher cooling demands and overheating due to climate change. They studied the thermal conditions of MURBs that meet the current National Energy Code of Canada for Buildings [55] and Passive House requirements [29]. A mid-rise and a high-rise MURB were used as case study buildings. Thermal conditions and overheating were defined according to ASHRAE 55 [53]. It was found that the number of overheating hours in buildings increased by 57% in future climate scenarios when considering buildings that meet current Passive House requirements, indicating that considering future climate conditions is critical when evaluating MURB retrofits.

Alavirad et al. [69] also investigated the performance of ECMs under future climate conditions through a case study of a Dutch neighborhood. A BPS study was performed in the Integrated Environmental Solutions Virtual Environment [70]. The KPIs monitored in this study were investment cost, heating and cooling loads, overheating risk, and investment cost per MWh reduced. The study found that improving the envelope insulation to reflect current regulations and adding an HRV reduced the space heating demand by 50 to 65%. Insulation upgrades to Passive House standards [29] reduced space heating demand by an additional 15%. They also found that sufficient ventilation eliminated the demand for space cooling with Passive House building envelopes. The results also showed that improvements to airtightness without an HRV can lead to overheating in future climates.

Furthermore, Shen et al. [71] studied the feasibility and importance of considering the impacts of climate change when analyzing building retrofits. They performed a parametric analysis of different retrofit options for existing buildings using EnergyPlus. The building envelope parameters that were examined in this study include window glazing units, wall insulation, roof insulation, window shading, air tightness, cooling supply air temperature setpoint, cooling system efficiency, heating system efficiency, lighting efficiency, and natural ventilation. The simulations were performed for San Francisco and Philadelphia, and future climate files were created using TMY3 weather data as a base, with the climatic variables replaced by data from the Hadley Centre Coupled Model version 3 [72] global climate model. They found that improvements to heating efficiency and roof insulation in residential buildings were effective in both current and future climate conditions. Improved air tightness and windows with lower SHGC also became more important in future climate scenarios. Wall insulation was found to be the least effective retrofit measure, as it helped reduce the heating energy demand but increased the cooling energy demand under future climate conditions.

The effectiveness of various retrofit measures is expected to change significantly under future climate conditions. While energy efficiency retrofits still benefit MURBs under future climate conditions, many of them lead to uncomfortable or dangerous indoor conditions. It is critical to understand these impacts to ensure the longevity of MURB retrofits.

The literature review informed the selection of mid-rise MURBs from the 1970s as the building archetype used in this study, due to their prevalence in Ontario and high energy consumption.

Several studies were identified that focused on reducing energy consumption and operational carbon emissions, which informed the focus of this study. Wall insulation, roof insulation, windows, and infiltration were common building envelope ECMs used in the studies reviewed; therefore, they were used in this analysis. Another common trend among retrofit projects was the mechanical upgrades necessary to achieve electrification. The lack of standardization for thermal comfort and thermal resilience metrics was apparent in this review; however, the SET metric was used in multiple studies and selected for evaluation in this study. The literature emphasized the importance of considering thermal comfort and resilience in deep energy retrofit projects. It is also crucial to verify that a retrofit will remain effective under future climate conditions.

### 3 Methodology

This chapter presents the methodology developed for this study, which builds upon the findings from the literature review. This involves creating a calibrated building energy model, developing a data-driven surrogate model for EUI prediction, and conducting an analysis of sequential retrofit strategies. The proposed methodology is designed to utilize freely available models and tools, be easily replicable, scalable to include additional performance metrics, and adaptable for broader retrofit evaluations. It aims to produce a practical and interpretable modelling framework that can be used by property owners, the City of Toronto, and other industry stakeholders to quickly and effectively assess the impact of various ECMs on building retrofit performance.

Note that an alternative modelling approach is employed to develop a generic model for MURBs, deviating from the common practice of constructing case-specific building energy models. Instead of developing a detailed numerical energy model that closely mimics the geometry and configuration of a specific case study MURB, an existing U.S. DOE archetype model is adopted. The selected archetype model represents a generic mid-rise MURB and was originally developed as part of the *DOE commercial prototype building models* [60]. This model serves as the foundation, and its parameters are adjusted to reflect the energy performance of the case study building. Modifications are limited to a set of physically meaningful and literature-supported parameters. These adjustments are made to align the model's monthly EUIs with those of the case study building, utilizing available utility data that includes monthly electricity and natural gas consumption. No modifications are made to the building geometry, fenestration layout, or zoning configuration.

This approach is pursued for two main reasons. First, using a reference archetype model instead of a detailed case-specific one enhances generalizability by avoiding dependence on unique building features. This enables broader application across similar MURBs, as will be demonstrated through the surrogate model development in this study. Second, detailed energy modelling is resource-intensive and often constrained by data gaps. Leveraging a well-documented archetype model with targeted, literature-supported adjustments streamlines calibration, making the method suitable for large-scale or early-stage assessments. Once calibrated, the model can serve as a “simulation engine” to generate synthetic data representing a

wide range of ECMs through a parametric analysis. The results of this parametric analysis are used to train a data-driven surrogate model for mid-rise MURBS in Toronto.

A surrogate building energy model (also known as a meta-model) is a simplified version of a more complex numerical model. It is typically based on statistical or machine learning techniques (such as regression or neural networks), and it is trained using data generated by detailed, physics-based building energy models (i.e., the archetype numerical model in this study). The goal is to mimic the behavior of the complex model while running significantly faster. This allows building stakeholders to explore different scenarios, optimize designs, or understand uncertainties without the high computational cost of running full simulations every time. For this study, the surrogate model can predict EUI for a given set of ECMs.

Finally, sequential retrofits are studied to evaluate the relative impact of the various ECMs. This sequence first implements retrofits targeting energy conservation (load reductions), followed by retrofits for energy efficiency (equipment upgrades). The models from the sequential retrofit study are simulated under both current and projected future climate conditions to determine the effectiveness of the ECMs as climate change progresses. The methodology is summarized in the flow chart in Figure 3.1.

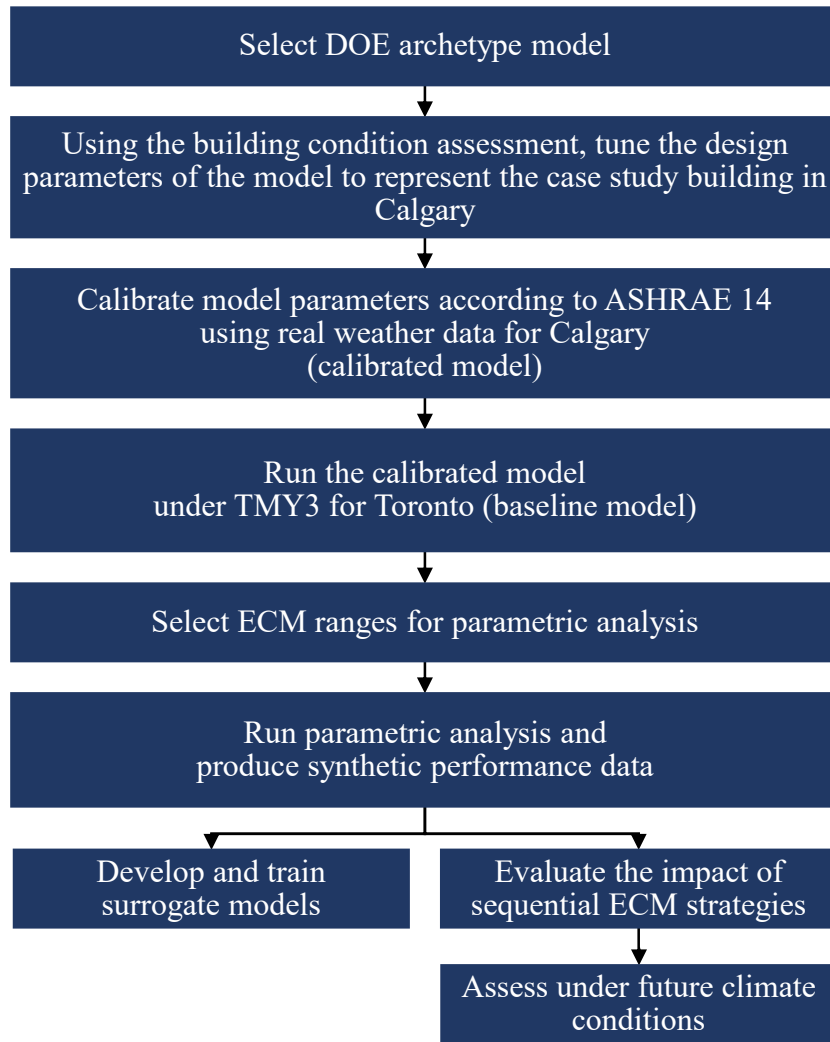


**Figure 3.1: Methodology Flow Chart**

### 3.1 Building Energy Model Development and Transfer to Target Climate

The first step of this study involves the development of a calibrated baseline energy model for a representative 1970s MURB in Toronto (ASHRAE Climate Zone 5A), to serve as the foundation for evaluating various retrofit strategies. In the absence of measured energy performance data from MURBs in Toronto of comparable vintage, calibration is instead performed using monthly utility data from a similar 1970s mid-rise MURB located in Calgary, Alberta (Climate Zone 7).

This approach is grounded in the assumption that MURBs of this era across major Canadian urban centers share comparable construction practices, building materials, HVAC system types, and occupancy behaviors, supported by nationwide building codes and development trends of the

time. Therefore, while climate differences exist, the building physics and operational characteristics are expected to remain largely consistent.

According to ASHRAE Guideline 14 [73], energy models intended for calibration should use measured weather data corresponding to the period of observed utility data. Accordingly, the model is calibrated using actual weather data from Calgary. However, once calibrated, it is common practice in both research and policy studies to use standard weather files such as TMY data to assess the impacts of ECMs under "average" climatic conditions. In recent years, projected future weather files have also been used to evaluate climate resilience and adaptation strategies [66].

Following this precedent, this study uses the calibrated model, originally developed using Calgary data, and only changes the weather data to Toronto TMY data to evaluate the effectiveness of ECMs in a Toronto climate context. This assumes that differences in climate are appropriately handled through the weather file and that the building characteristics remain applicable due to their archetypal nature.

A comparative analysis of monthly heating degree days (HDD, base 18°C) and cooling degree days (CDD, base 18°C) supports the viability of this approach. This analysis is presented in Appendix A. The statistical differences in degree-days between Calgary's current climate and Toronto's current climate are generally smaller, or comparable, to those between Toronto's current climate and its projected future climate (GW3.5). For RMSE, Calgary's current climate is closer to present-day Toronto for both HDD and CDD. For MBE, the CDD bias is notably smaller for the Toronto–Calgary comparison, while the HDD bias is of similar magnitude in both comparisons. Given that future climate files, with their larger overall deviations from present conditions, are increasingly accepted for use in calibrated models, these results suggest that using calibration data derived from Calgary and subsequently adjusted with Toronto weather files could introduce no greater temperature-driven uncertainty than the accepted practice of using future climate scenarios. This approach may be well-suited for creating synthetic datasets to support surrogate modeling; however, it is not intended for use in regulatory or certification contexts (such as compliance modeling or incentive programs), where precise, location-specific, and project-specific calibration is mandatory.

This calibrated version, referred to as the **calibrated model**, is adjusted to match the monthly EUI of the Calgary case study building by modifying parameters such as infiltration, envelope thermal properties, and HVAC system type while maintaining the archetype geometry. Once calibrated under Calgary conditions, the model is transferred to Toronto by replacing the Calgary weather file with the Toronto weather file. This model version is referred to as the **baseline model**.

### 3.1.1 EnergyPlus

The building performance simulation tool used in this study is EnergyPlus (version 24.1.0) [59]. EnergyPlus is a whole-building energy simulation program developed by the U.S. Department of Energy (DOE) to extend previous programs such as Basic Local Alignment Search Tool (BLAST) and DOE-2 [74]. It is one of the most widely used energy simulation tools [75] among engineers, architects, and researchers for modelling both energy consumption and water use. It considers factors such as space conditioning, equipment, lighting, occupants, and outdoor conditions. It is an open-source console-based simulation engine that uses two input files: an input data file (IDF) and an EnergyPlus weather (EPW) file [59]. The IDF file is a text file that contains information regarding the building's geometry, envelope parameters, HVAC systems, and other building systems. The EPW file is a text file that contains meteorological hourly weather data for a typical year [76]. EnergyPlus implements building physics for air, moisture, and heat transfer through numerical modelling. It can estimate the heating and cooling loads required to maintain thermal control setpoints. It can also calculate thermal comfort metrics, as well as lighting, shading, and daylighting conditions. It supports many HVAC systems and components, and it can simulate sub-hourly time steps to capture fast dynamics [77]. The EnergyPlus simulation engine has undergone extensive validation, some of which can be found [here](#)<sup>1</sup>. In a study of building energy model calibration, Royapoor et al. [78] found EnergyPlus provided very accurate results relative to actual consumption, with electricity use being under-predicted by only 1.08% and natural gas use being over-predicted by only 3.8%. Similarly, Haves et al. [79] found that EnergyPlus over-predicts the cooling load and under-predicts the heating load by only 1.5%.

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<sup>1</sup> Lawrence Berkeley National Laboratory. *EnergyPlus Validation Reports* (Accessed July 2025). [https://simulationresearch.lbl.gov/dirpubs/valid\\_ep.html](https://simulationresearch.lbl.gov/dirpubs/valid_ep.html)

### 3.1.2 Archetype Energy Model

The archetype model used in this study is a U.S. DOE building energy model of a typical mid-rise MURB developed by the Pacific Northwest National Laboratory (PNNL) with input from the ASHRAE 90.1 Standards committee [60]. The archetype used is a commercial prototype building model, developed per the 2004 edition of ASHRAE Standard 90.1. This is the oldest edition of ASHRAE Standard 90.1 for which the DOE has provided models, which requires fewer adjustments to represent the performance of a 1970s vintage MURB. The building type is titled “Mid-rise Apartment”, and the climate zone 5A (Buffalo) model is selected as an **archetype model**. The use of a DOE model provides a consistent model reference for future studies.

The DOE archetype model is a 4-storey MURB with 23 units and an office. The building's footprint is 783.7 m<sup>2</sup> (8,436 ft<sup>2</sup>), and each floor features eight one-bedroom units (except the main floor, which has seven one-bedroom units and an office), as well as a service corridor. The archetype model has natural gas space heating, electric space cooling, and electric DHW. Figure 3.2 shows a three-dimensional model of the DOE archetype [60]. Note that the DOE archetype model's geometry is unchanged throughout this study; however, the building envelope specifications, mechanical system specifications, and space heating schedule are modified through the model calibration process to represent the case study building presented in the following section.

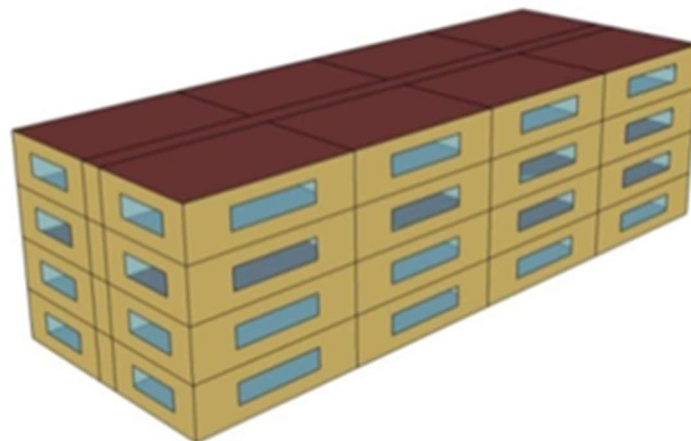


**Figure 3.2: U.S. DOE Archetype Energy Model**

### 3.1.3 Case Study Building

Actual building energy consumption data is required to calibrate a building energy model. The available data is for a mid-rise MURB in Calgary, Alberta, and consists of monthly natural gas and electricity bills, as well as a condition assessment performed in 2020 [80]. This building has a ground-floor parking garage and six residential floors. The footprint of the building is approximately 464.5 m<sup>2</sup> (5000 ft<sup>2</sup>), and each floor has six units (three 1-bedroom and three 2-bedroom units). Each unit has a balcony, and several other tall buildings surround the building. The case study building uses a natural gas-fired boiler for heating and DHW and has no cooling system. Figure 3.3 shows an image of the case study building. A comprehensive comparison of the archetype energy model and the case study building is presented in Table B.1 in Appendix B.



**Figure 3.3: The 1970s Case Study Mid-Rise Multi-Unit Residential Building**

### 3.1.4 Input Weather File for Calibration

The weather file used to calibrate the model contains actual weather data corresponding to the period during which the energy consumption data of the case study building was collected (April 2020 to March 2021). The weather data is collected from the Calgary International Airport weather station and includes the dry bulb temperature, dew point temperature, and relative humidity for the reference period [81]. It should be noted that actual solar irradiance data is not

available; therefore, the solar irradiance values from the Calgary Intl TMY weather file (CAN\_AB\_Calgary.Intl.AP.718770\_TMYx.zip) [82] are used. It is assumed that this has a negligible impact, as the reference building has balconies and is surrounded by tall buildings that provide shading; therefore, minimal solar gains are expected.

### **3.1.5 Model Calibration<sup>2</sup>**

To calibrate the archetype model, the simulated natural gas and electricity consumptions (normalized by conditioned floor area) are compared to the actual natural gas and electricity consumptions of the case study building, as recorded in the utility bills (also normalized by conditioned floor area). The archetype model is calibrated to the monthly ASHRAE 14 calibration requirements, which require a normalized mean bias error (NMBE) of  $\leq 5\%$  and a coefficient of variation of the root mean squared error (CVRMSE) of  $\leq 15\%$  between the simulated and actual fuel consumptions [73].

Note that the mechanical systems of the archetype model are modified to represent the case study building, based on the information provided in the condition assessment. The case study building has no cooling; therefore, the cooling is shut off for the archetype model. The case study building uses natural gas for DHW; therefore, the DHW in the archetype model is switched from electricity to natural gas. Considering that taller neighboring buildings surround the case study MURB and that 1.5-meter-deep balconies shade its south-facing windows and balcony doors, an adjusted SHGC value of 0.1 was assumed in the archetype model. A more precise estimate could be obtained through a seasonal shading analysis, as proposed by Kohler et al. [83], provided that hourly energy consumption data is available, which was not the case for this case study.

After making these changes to the archetype model, several building parameters are adjusted to calibrate the electricity and natural gas consumptions with those of the case study building. These parameters include the electric equipment peak loads, DHW and heating efficiency, DHW peak flow rate, thermal resistance of the wall and roof insulation (i.e., R-value), and infiltration.

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<sup>2</sup> The term ‘calibration’ in this research follows the convention used in ASHRAE Guideline 14, where it generally refers to adjusting model parameters based on observed data to improve predictive performance. However, from a statistical perspective, ASHRAE 14 primarily defines a validation protocol, even though the building energy modelling community commonly refers to this process as ‘calibration.’

Monthly electricity consumption is calibrated first, as adjustments to electric equipment loads can impact the internal gains of the zones and, in turn, the natural gas consumption for space conditioning. As there is no electric space conditioning, electricity consumption consists only of base loads (lighting and equipment). To modify the base loads, LPD and EPD are adjusted until the monthly electricity consumption achieves ASHRAE 14 calibration.

Next, the natural gas base load (DHW) consumption is calibrated. As there is no natural gas consumption in the summer attributed to space conditioning, all the natural gas consumption in the summer can be attributed to DHW. The DHW efficiency and peak flow rate are adjusted until the simulated natural gas consumption in the summer matches the actual natural gas consumption of the case study building. The natural gas base load is assumed to remain relatively constant throughout the year.

Finally, the variable (space heating) natural gas consumption is calibrated. The wall and roof insulation, infiltration, and heating efficiency are adjusted to achieve ASHRAE 14 calibration for the monthly natural gas consumption. This process is summarized in Figure 3.4.

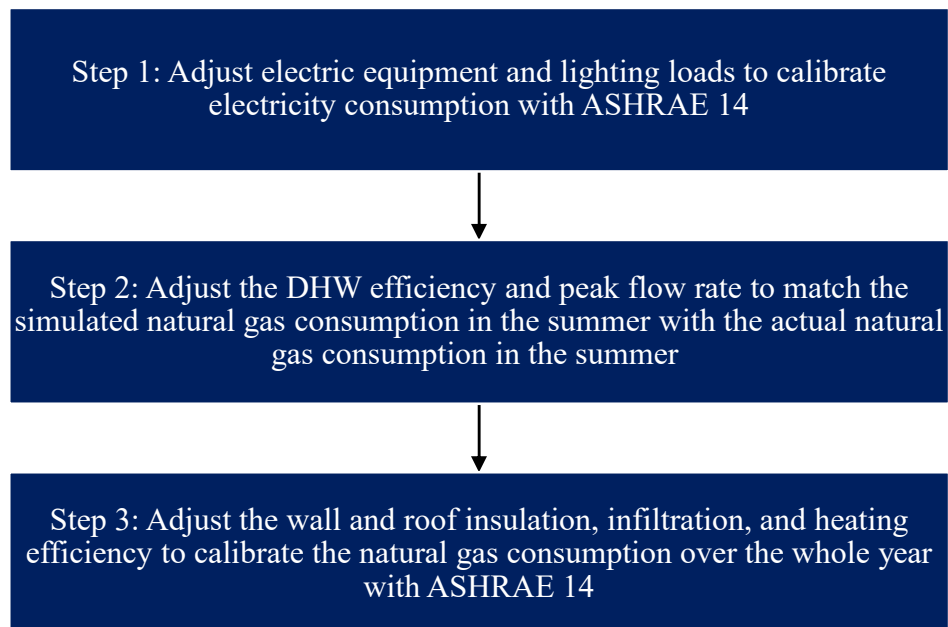


**Figure 3.4: Model Calibration Process**

## 3.2 Parametric Analysis

The next step in this study involves transferring the calibrated model to Toronto. This is done by replacing the Calgary weather file with the TMY for Toronto (CAN\_ON\_Bishop-Toronto.City.AP.712650\_TMYx) under current climate conditions (derived from hourly weather data through 2023) [82]. This **baseline model** now represents a 1970s mid-rise MURB in Toronto. A parametric analysis is conducted using the baseline model to determine how various ECMs impact the KPIs: energy efficiency, decarbonization, thermal stress, and thermal resilience.

### 3.2.1 Energy Conservation Measures

The ECMs evaluated in this study include the effective thermal resistance (R-value) of the wall assembly, the effective thermal resistance (R-value) of the roof assembly, the window thermal conductance (U-factor), infiltration, lighting power density (LPD), equipment power density (EPD), and DHW peak flow rate. In addition, three different HVAC systems are evaluated, as summarized in Table 3.1. The space cooling in HVAC B and HVAC C is available from May 1<sup>st</sup> to October 31<sup>st</sup>. The ventilation in HVAC C is available for the entire year.

**Table 3.1: HVAC Systems & Fuel Types**

|                                   | <b>Primary<br/>Space Heating</b> | <b>Auxiliary<br/>Space Heating</b> | <b>Space<br/>Cooling</b> | <b>Domestic<br/>Hot Water</b>    | <b>Mechanical<br/>Ventilation</b> |
|-----------------------------------|----------------------------------|------------------------------------|--------------------------|----------------------------------|-----------------------------------|
| HVAC A<br>(existing)              | Natural Gas<br>Furnace           | N/A                                | N/A                      | Natural Gas<br>Boiler            | N/A                               |
| HVAC B<br>(partially<br>electric) | Electric<br>ASHP                 | Natural Gas<br>Furnace             | Electric<br>ASHP         | Natural Gas<br>Boiler            | N/A                               |
| HVAC C<br>(fully<br>electric)     | Electric<br>ASHP                 | Electric<br>Baseboard<br>Heaters   | Electric<br>ASHP         | Electric<br>Resistance<br>Boiler | ERV                               |

While literature shows that external shading and WWR also have a significant impact on building energy consumption, the balconies eliminate the need for an external shading retrofit, and WWR is not typically changed in retrofit scenarios. Thus, these ECMs are not evaluated.

### 3.2.2 Key Performance Indicators

The metrics in Table 3.2 are selected to assess the impact of the various MURB retrofit designs on the KPIs: energy efficiency, decarbonization, thermal stress, and thermal resilience.

**Table 3.2: Key Performance Indicator Metrics**

| KPI                | Metric                                                                     |
|--------------------|----------------------------------------------------------------------------|
| Energy Efficiency  | EUI [kWh/m <sup>2</sup> ] [BTU/ft <sup>2</sup> ]                           |
|                    | Energy Consumption by End Use [kWh/m <sup>2</sup> ] [BTU/ft <sup>2</sup> ] |
|                    | Peak Heating Demand [kW] [BTU/hr]                                          |
|                    | Peak Cooling Demand [kW] [BTU/hr]                                          |
| Decarbonization    | Annual Carbon Emissions [metric tonnes CO <sub>2</sub> e]                  |
| Thermal Stress     | Humidity Index [hr]                                                        |
|                    | SET [°·hr]                                                                 |
| Thermal Resilience | Hours of Safety for Cold Events [hr]                                       |
|                    | Hours of Safety for Heat Events [hr]                                       |

Thermal resilience is gaining recognition as an important KPI due to the increasing number of extreme weather events and the projected increase in GSAT. The industry still needs to develop a standardized method for assessing thermal vulnerability, including: (1) a well-defined set of thermal resilience metrics that can be quantified through measurements or building performance simulation, and (2) standardized definitions and datasets of extreme temperature events covering major global cities [84]. In this study, the hours of safety for cold events represent the number of hours in the year where the average indoor temperature is greater than or equal to 16°C, and the hours of safety for heat events represent the number of hours in the year where the average indoor temperature is less than or equal to 30°C [85].

### 3.2.3 ECM Value Selection

An industry scan is conducted, and various high-performance building programs and standards are referenced to establish the ECM upgrade values, including baseline design values. Table B.2 in Appendix B summarizes this research. The ranges of values used for each building retrofit parameter are presented below in Table 3.3.

**Table 3.3: Building Retrofit Parameter Ranges Simulated**

| <b>Retrofit Parameter<br/>(Baseline and ECMs)</b> | <b>Range of Values Simulated (SI)</b> | <b>Range of Values Simulated (IP)</b>                   |
|---------------------------------------------------|---------------------------------------|---------------------------------------------------------|
| Total Window Thermal Conductance                  | 0.568 to 3.407 W/m <sup>2</sup> ·K    | 0.1 to 0.6 BTU/ft <sup>2</sup> ·°F·h                    |
| Wall Thermal Resistance                           | 0.704 to 7.045 m <sup>2</sup> ·K/W    | 4 to 40 ft <sup>2</sup> ·°F·h/BTU                       |
| Roof Thermal Resistance                           | 0.704 to 10.567 m <sup>2</sup> ·K/W   | 4 to 60 ft <sup>2</sup> ·°F·h/BTU                       |
| Infiltration per Exterior Surface Area            | 0.16 to 0.62 L/s·m <sup>2</sup>       | 0.000525 to 0.002034 ft <sup>3</sup> /s·ft <sup>2</sup> |
| LPD                                               | 2 to 12 W/m <sup>2</sup>              | 0.63 to 3.80 Btu/h·ft <sup>2</sup>                      |
| EPD                                               | 4 to 20 W/m <sup>2</sup>              | 1.27 to 6.34 Btu/h·ft <sup>2</sup>                      |
| DHW Peak Flow Rate                                | 0.0013 to 0.0021 L/s·person           | 0.020 to 0.034 gallons/min·person                       |

Latin Hypercube Sampling (LHS) is used to generate the parameter value sets used in the parametric analysis. LHS stratifies each input variable range into 700 intervals. Next, it randomly selects one value from each interval and then randomly assembles sets of parameters containing each input variable. The use of LHS minimizes the computational demand of the parametric analysis while ensuring adequate coverage of the parameter space, making it well-suited for training data-driven surrogate models. Based on research performed by Westermann et al. [86], 100 samples per continuous retrofit parameter using LHS is more than sufficient to train the surrogate model. In this study, there are seven continuous retrofit parameters; therefore, 700 building simulations were performed for each of the three HVAC systems, leading to a total of 2,100 building simulations. This sampling strategy is designed to adequately capture the interactions and non-linearities across the seven-dimensional ECM space, with each ECM treated as an independent input dimension. A custom Python script was used to automatically perform the LHS, generate and run all retrofit scenarios, and post-process the output data. This script is included in section C.2.2 of 0.

### 3.2.4 Surrogate Modelling

Surrogate models for each of the three HVAC systems are trained to predict the EUI of a mid-rise MURB for different ECM values within the scope of this study. For each HVAC system, an artificial neural network model and polynomial models are trained. These models are created and trained using tools from the Scikit Learn Python library [87]. The surrogate models for each of the three HVAC systems are trained on their respective 700 samples. First, the data is split into

90% training data and 10% validation data. Next, the surrogate model inputs, the ECMs, are standardized to increase the accuracy of the trained model. An exhaustive search with 10-fold cross-validation is used to determine an optimal surrogate model estimator and hyperparameters. Two types of estimators are evaluated, including polynomial regression and multi-layer perceptron (MLP). For each estimator type, a range of hyperparameters is evaluated to optimize model performance. For polynomial regression, this includes the degree of the polynomial. For MLP, this includes the number of hidden layers, initial learning rate, regularization parameter (alpha), and the optimization algorithm (solver).

The parametric analysis and surrogate model training process are performed using Python (version 3.12) [88] in Visual Studio Code [89]. In this study, several standard Python libraries are utilized, as documented in the code provided in Appendix C.2. The *main.py* file, located in Appendix C.2.1, establishes the file paths for EnergyPlus, the inputs, and outputs, and it invokes functions defined in other files. The *parameterize\_functions.py* file, located in Appendix C.2.2, contains functions to perform LHS based on the information provided in the *inputs.csv* file, create IDF files, and execute IDF files. The *postprocess\_results.py* file, located in Appendix C.2.3, contains functions to read the CSV or SQL files generated by EnergyPlus and extract specific results into an output CSV file. Finally, the *surrogate\_model.py* file, located in Appendix C.2.4, contains functions for training surrogate models and evaluating their performance.

### 3.3 Sequential Retrofits

A sequential retrofit analysis is performed to evaluate the impact of the retrofits on both EUI and the other KPIs. The first step in this sequence involves improving energy conservation, which includes upgrades to the building envelope. This is followed by improving energy efficiency through mechanical system upgrades. In addition to upgrades that minimize EUI, some upgrades are included to reduce thermal stress, enhance thermal resilience, and lower carbon emissions. The final step in the sequential retrofits is reducing the EPD, LPD and DHW peak flow rate to ASHRAE 90.1 values, 6.67 W/m<sup>2</sup>, 2.15 W/m<sup>2</sup>, and 0.00013 L/s/person, respectively [90]. The sequential retrofits are outlined in Figure 3.5.

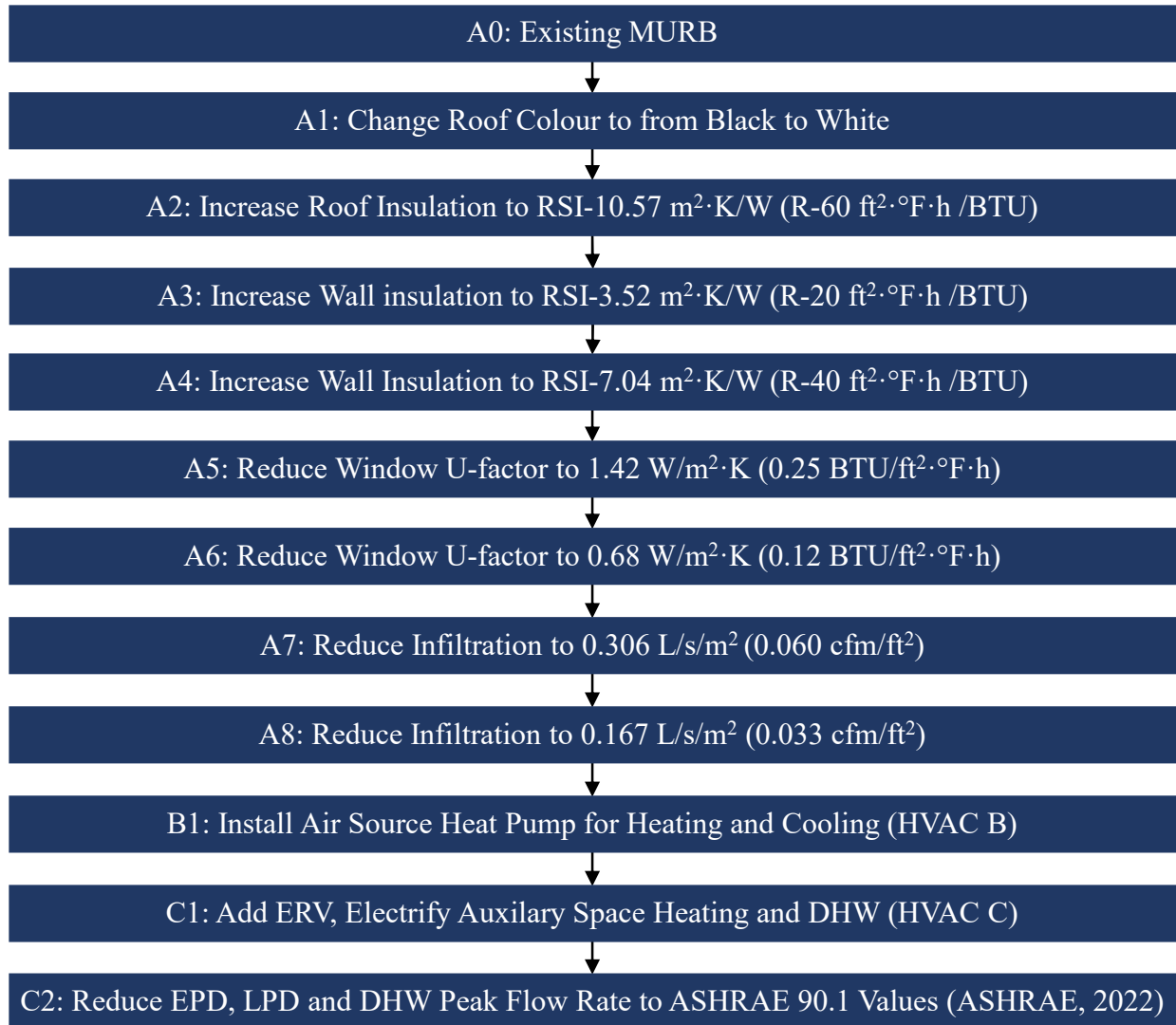


**Figure 3.5: Sequential Retrofits**

### 3.4 Future Climate Analysis

The sequential retrofits are also evaluated using a future climate weather file. The National Research Council has developed future climate files ranging from 0.5°C to 3.5°C global warming scenarios [91]. These files include updated design day conditions that are used for HVAC sizing. The 3.5°C scenario is selected to capture the impact of future climate conditions using a high-emissions scenario (Representative Concentration Pathway 8.5), which projects an increase in Ontario's annual mean temperature of at least 3.5 °C by 2080. The future climate scenario is used to assess how the sequential retrofits will impact the MURB's energy

consumption, thermal resilience, and thermal stress as the climate continues to warm. For energy consumption, a decrease in natural gas consumption for heating and an increase in electricity consumption for cooling are anticipated. For thermal resilience, it is assumed that the hours of safety for heat events will decrease under the 3.5°C global warming scenario. For thermal stress, an increase in uncomfortable and dangerous humidex hours, as well as an increase in SET degree-hours, is anticipated under future climate conditions.

## 4 Results & Analysis

This chapter presents an analysis of the results of this study. This includes the details of the baseline model calibration, the surrogate model training process, the sequential retrofit impacts, and the future climate study. Where applicable, the results have been normalized to enhance interpretability and facilitate comparison.

### 4.1 Baseline Model Calibration

The ASHRAE 14 monthly calibration methodology was followed to calibrate the archetype model to the case study building utility data [73]. The calibrated model achieved an NMBE of 3.35% ( $\leq 5\%$ ) and CVRMSE of 4.36% ( $\leq 15\%$ ) for electricity consumption, and an NMBE of 4.76% ( $\leq 5\%$ ) and CVRMSE of 14.91% ( $\leq 15\%$ ) for natural gas consumption. The building parameters for the baseline model are detailed in Table 4.1. A comparison of the parameters of the DOE model and the baseline model are detailed in Table B.2 in Appendix B.

**Table 4.1: Calibrated Parameters for the Baseline Numerical Model**

| Parameter          | Value (SI)                       | Value (IP)                                  |
|--------------------|----------------------------------|---------------------------------------------|
| LPD                | 5 W/m <sup>2</sup>               | 1.58 BTU/ft <sup>2</sup> ·h                 |
| EPD                | 7 W/m <sup>2</sup>               | 2.22 BTU/ft <sup>2</sup> ·h                 |
| DHW Peak Flow Rate | 0.0052 l/s                       | 0.00018 ft <sup>3</sup> /s                  |
| DHW Efficiency     | 75%                              |                                             |
| Window U-Factor    | 3.38 W/m <sup>2</sup> ·K         | 0.59 BTU/ ft <sup>2</sup> ·°F·h             |
| Wall R-Value       | 0.80 m <sup>2</sup> ·K/W         | 4.54 ft <sup>2</sup> ·°F·h/BTU              |
| Roof R-Value       | 1.92 m <sup>2</sup> ·K/W         | 10.90 ft <sup>2</sup> ·°F·h/BTU             |
| Infiltration       | 0.611 l/s· m <sup>2</sup>        | 0.002005 ft <sup>3</sup> /s·ft <sup>2</sup> |
| Roof Colour        | Black (Solar Absorptance of 0.7) |                                             |
| Heating System     | Natural Gas Furnace              |                                             |
| Heating Efficiency | 60%                              |                                             |
| Cooling System     | N/A                              |                                             |
| Ventilation System | N/A                              |                                             |

The monthly electricity and natural gas EUIs for the case study building and the calibrated model are presented in Figure 4.1 and Figure 4.2. The electricity consumption remained relatively constant throughout the year as electricity was not used for space conditioning. Natural gas consumption peaked in February due to lower-than-average temperatures, which led to increased heating demand. During the summer, the natural gas consumption corresponded to the DHW base load and remained relatively constant. The simulation accurately captured this behaviour to meet the ASHRAE 14 calibration requirements.

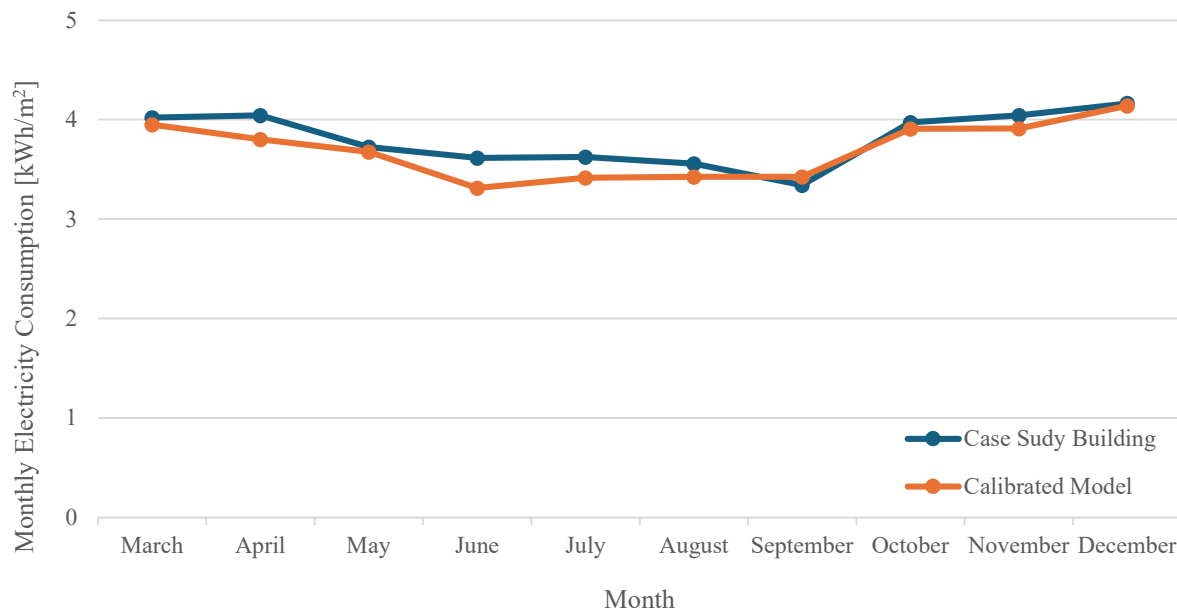


**Figure 4.1: Electricity Calibration**

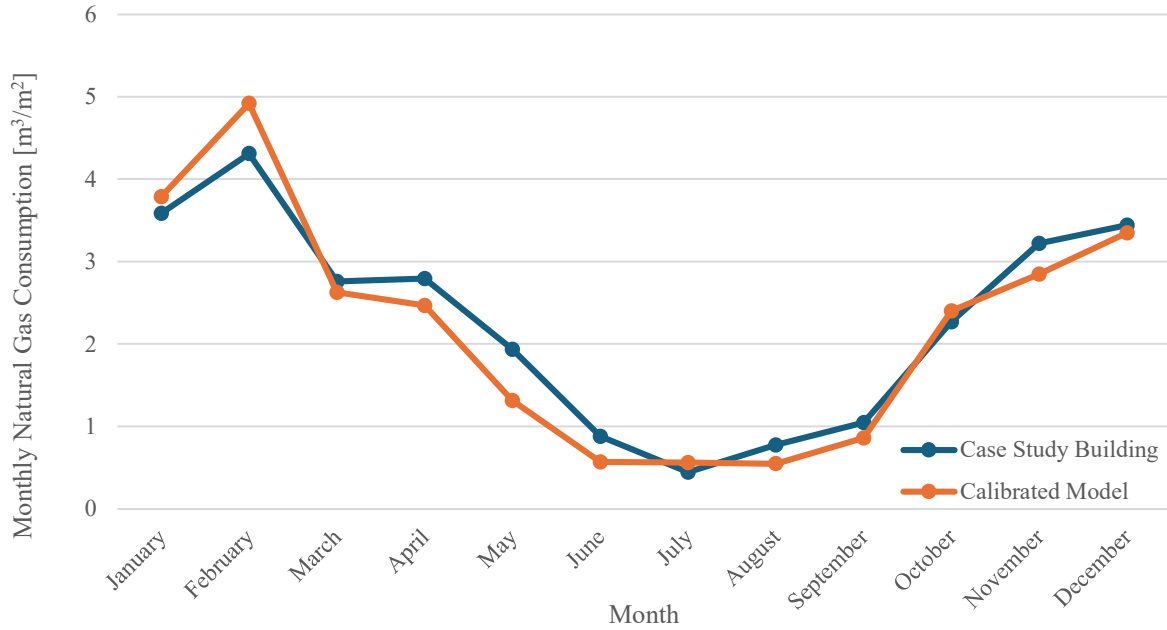


**Figure 4.2: Natural Gas Calibration**

## 4.2 Surrogate Modelling

The surrogate modelling process produced MLP and polynomial regression surrogate models that can be used to predict EUI for similar mid-rise MURBs. The surrogate models were scored based on their coefficients of determination ( $R^2$  values). The results of this training process are compared in Table 4.2. The best-performing surrogate model for all HVAC systems was the MLP; however, the polynomial regression models also performed very well, demonstrated by their high  $R^2$  values.

**Table 4.2:  $R^2$  Values of Surrogate Models**

|                          | HVAC A        | HVAC B        | HVAC C        |
|--------------------------|---------------|---------------|---------------|
| <b>MLP</b>               | <b>99.98%</b> | <b>99.99%</b> | <b>99.99%</b> |
| First-Degree Polynomial  | 92.89%        | 98.50%        | 98.91%        |
| Second-Degree Polynomial | 98.63%        | 99.76%        | 99.80%        |
| Third-Degree Polynomial  | 98.92%        | 99.88%        | 99.81%        |
| Fourth-Degree Polynomial | 99.92%        | 99.98%        | 99.99%        |
| Fifth-Degree Polynomial  | 99.43%        | 99.91%        | 99.86%        |

### 4.2.1 Hyperparameter Tuning

The validation curves for the MLP surrogate model training are shown below in Figure 4.3, Figure 4.4, and Figure 4.5. These curves illustrate the impacts of the models' hyperparameters on their performances. The MLP hyperparameters studied included the solver, regularization parameter (alpha), activation function, and hidden layer sizes. The model validation curves indicate that the activation function and solver have the greatest impact on the surrogate model's performance, with the ReLU activation function and the LBFGS solver resulting in the highest cross-validation scores. The cross-validation scores had very little sensitivity to the hidden layer sizes and regularization.

The training score (blue line) reflects the model's performance on the data it was trained on. The cross-validation score (orange line) reflects the model's performance on new data. When interpreting validation curves, the relationship between the training and cross-validation scores provides important insights into the model's behaviour. A high training score, coupled with a significantly lower cross-validation score, typically indicates overfitting, where the model memorizes the training data but fails to generalize effectively. This often occurs when training a complex model with an insufficient amount of training data. Conversely, low scores on both curves suggest underfitting, where the model is too simple to capture the underlying structure of the data. In this study, the training and cross-validation score curves are closely aligned, indicating that the model generalizes well and does not suffer significantly from either overfitting or underfitting, a sign of a well-fitted model. It is also important to minimize the standard deviation of the scores (orange and blue shaded regions), as this indicates the model's sensitivity to the selection of training data.

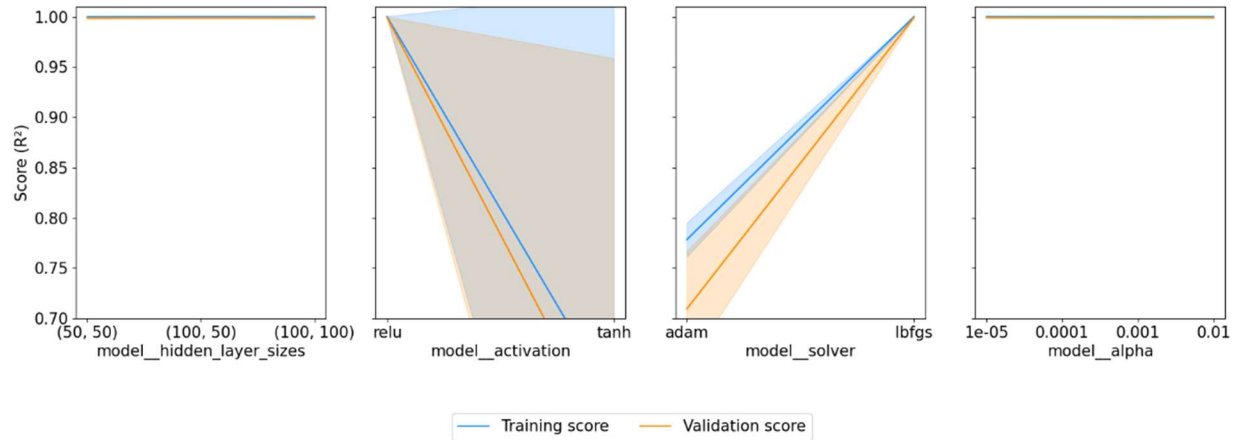


**Figure 4.3: HVAC A MLP Surrogate Model Validation Curves**

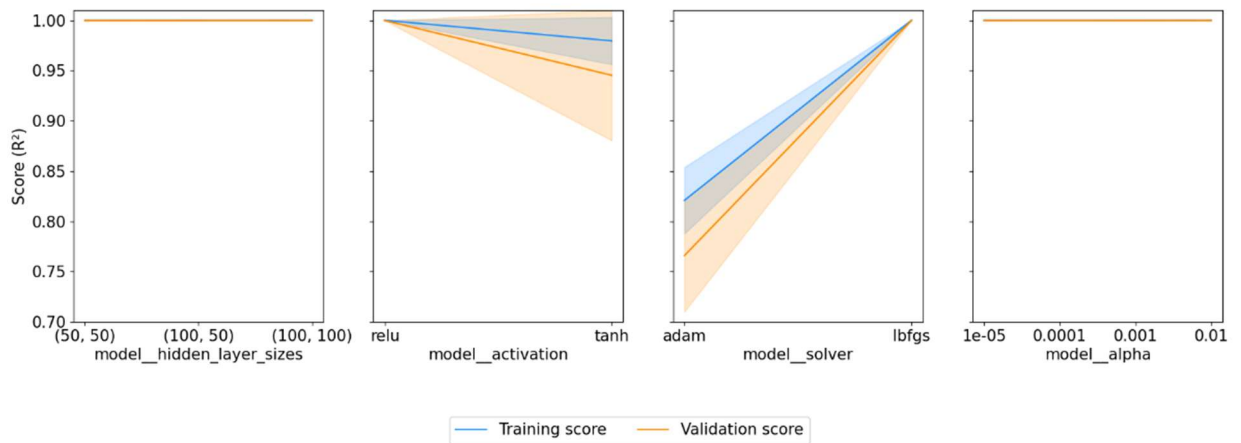


**Figure 4.4: HVAC B MLP Surrogate Model Validation Curves**

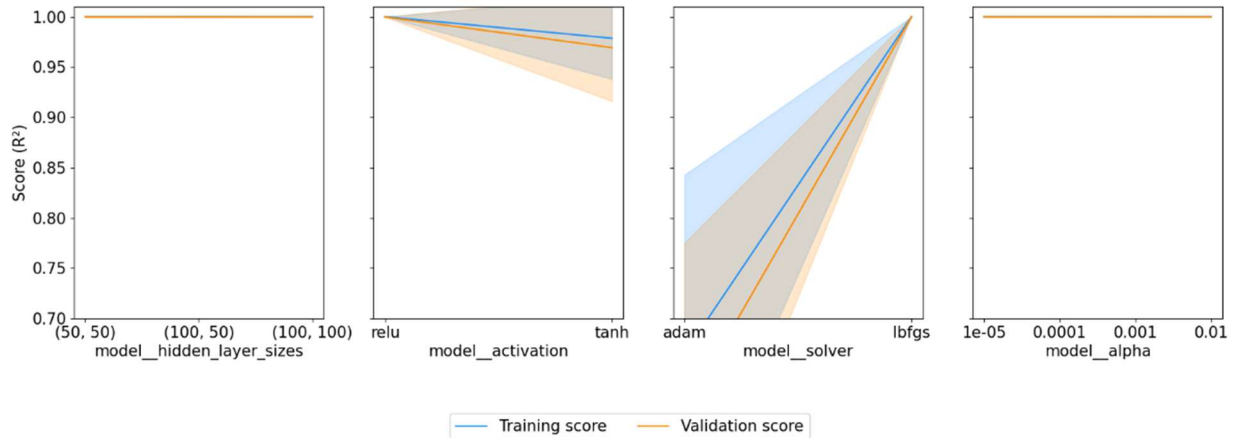


**Figure 4.5: HVAC C MLP Surrogate Model Validation Curves**

The final tuned hyperparameters of the MLP surrogate models are summarized in Table 4.3 below.

**Table 4.3: MLP Surrogate Models Tuned Hyperparameters**

|                     | HVAC A                                                  | HVAC B     | HVAC C     |
|---------------------|---------------------------------------------------------|------------|------------|
| Hidden Layer Sizes  | (100, 50)                                               | (100, 100) | (100, 100) |
| Activation Function | Rectified Linear Unit (ReLU)                            |            |            |
| Solver              | Limited-memory Broyden–Fletcher–Goldfarb–Shanno (LBFGS) |            |            |
| Regularization      | 0.0001                                                  | 0.001      | 0.0001     |

The validation curves for the polynomial regression surrogate models are shown below in Figure 4.6, Figure 4.7, and Figure 4.8. The polynomial regression hyperparameter studied was the polynomial degree. The polynomial degree had a significant impact on the performance of the surrogate models. The second-, third-, fourth-, and fifth-degree polynomials performed very well with high cross-validation scores (>98%) and low standard deviations. As expected, the first-degree polynomial surrogate models did not perform as well. An interesting development was that the fifth-degree polynomials performed slightly worse than the fourth-degree polynomials, despite having a higher degree. This was because the fifth-degree polynomial model was more complex and required more training data. The model was slightly overfit and did not perform as well on new data, as illustrated by the lower cross-validation score (orange line) compared to the

training score (blue line). For all three HVAC systems, the best-performing polynomial regression models were the fourth-degree models; however, the second and third-degree models also performed very well and are much simpler to use. The equations for the second, third, and fourth-degree polynomial surrogate models are included in section Appendix C.1. They can be used to predict the EUI of mid-rise MURBs in the City of Toronto, within the range of ECM values used for training.

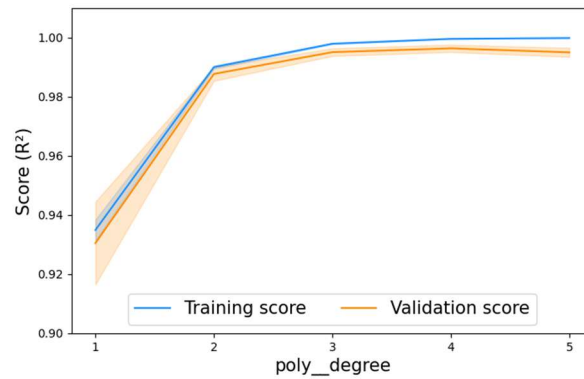


**Figure 4.6: HVAC A Polynomial Regression Surrogate Model Validation Curves**

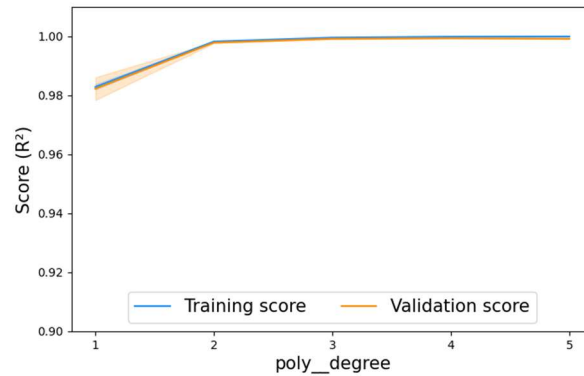


**Figure 4.7: HVAC B Polynomial Regression Surrogate Model Validation Curves**

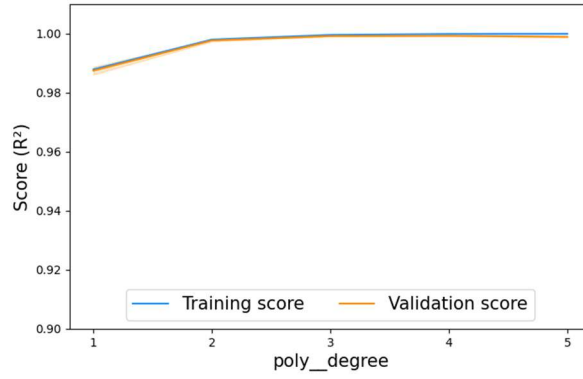


**Figure 4.8: HVAC C Polynomial Regression Surrogate Model Validation Curves**

#### 4.2.2 Dataset Size Sensitivity Analysis

A sensitivity analysis was performed to determine the optimal size of the training data for MLP and polynomial regression surrogate models, aiming to evaluate the impact of the training dataset size on the models' performance. The models were trained on increasingly large subsets of the training data, and their scores ( $R^2$  values) were evaluated. The learning curves for the MLP surrogate models in Figure 4.9, Figure 4.10, and Figure 4.11 show that the scores ( $R^2$  values) plateau at approximately 150 samples. Therefore, the 700 total samples used in this study were more than sufficient to train an accurate surrogate model. Similarly, the learning curves for the fourth-degree polynomial regression surrogate models in Figure 4.12, Figure 4.13, and Figure 4.14 show that the scores ( $R^2$  values) plateau at approximately 200 to 400 samples.

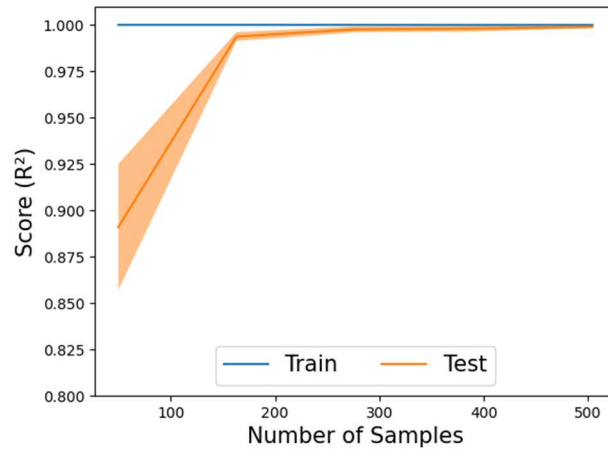


**Figure 4.9: HVAC A MLP Surrogate Model Learning Curve**

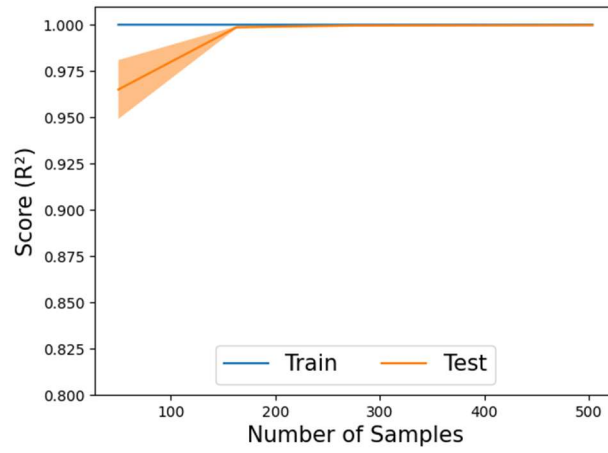


**Figure 4.10: HVAC B MLP Surrogate Model Learning Curve**

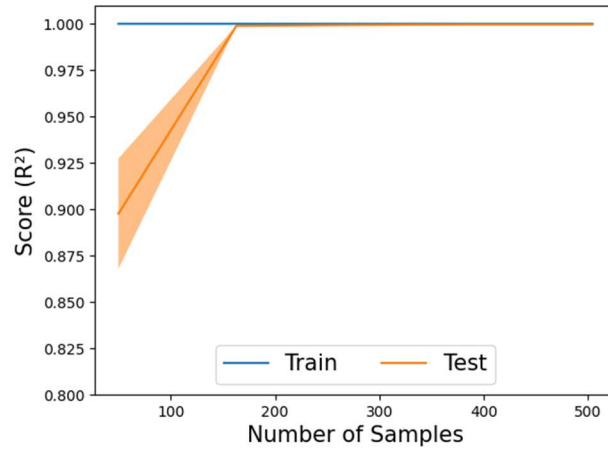


**Figure 4.11: HVAC C MLP Surrogate Model Learning Curve**

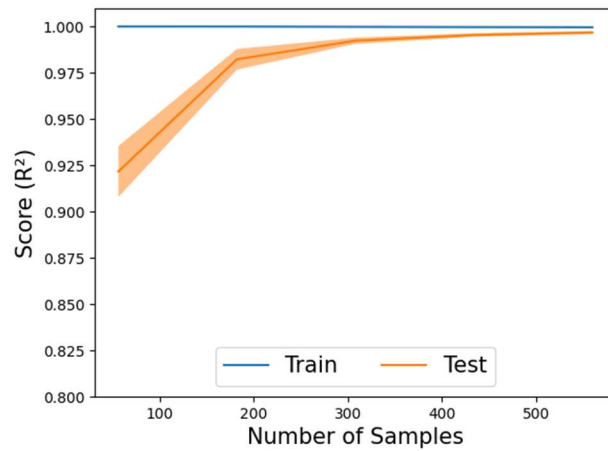


**Figure 4.12: HVAC A Polynomial Regression Surrogate Model Learning Curve**

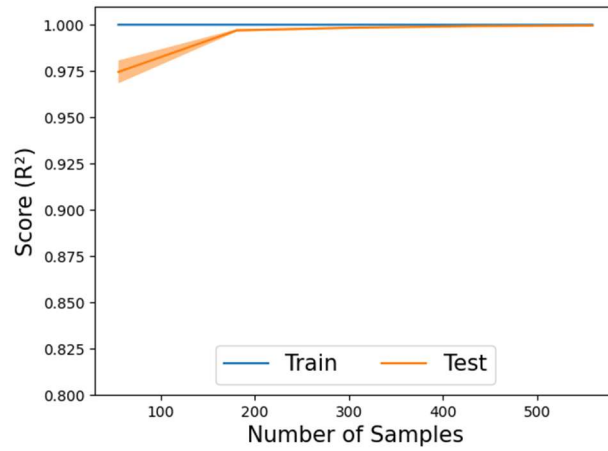


**Figure 4.13: HVAC B Polynomial Regression Surrogate Model Learning Curve**

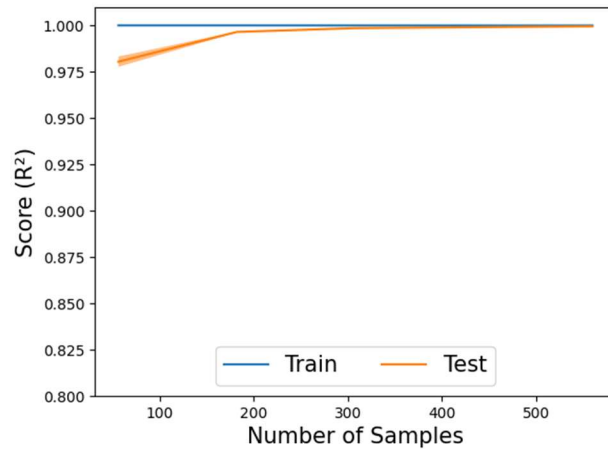


**Figure 4.14: HVAC C Polynomial Regression Surrogate Model Learning Curve**

### 4.2.3 Metrics on Validation Data

The surrogate models were then evaluated based on their performance on a set of validation samples (70 samples for each HVAC system, 10% of the LHS data that was withheld during training), which were withheld throughout the entire training process. The statistical metrics of these results are detailed in Table 4.4, Table 4.5, and Table 4.6. (for HVAC systems A, B, and C, respectively) for comparison with other studies. All the MLP and fourth-degree polynomial models achieved  $R^2$  values greater than 99.80% on the validation set; therefore, the models can be considered accurate and reliable within the range of the input parameters presented in

Table 3.3. The direction (positive or negative) of the MBE varied between the models, and the magnitudes of the NMBE for the MLP and fourth-degree polynomial models were less than 0.05%, indicating that neither model consistently overestimated nor underestimated the EUI. The mean absolute error (MAE) of the MLP and fourth-degree polynomial models was less than 2.9 kWh/m<sup>2</sup>, indicating that the surrogate model predictions do not deviate significantly from the validation data. The root mean squared error (RMSE) and the normalized root mean squared error (NRMSE) both measure the error of the models and penalize larger errors. The NRMSE of the MLP and fourth-degree polynomial models was less than 0.6%, indicating that the models do not exhibit significant errors. Note that while these statistical metrics provide an overall evaluation of the surrogate models, local prediction errors near the minimum and maximum values of the training parameter ranges tend to be larger. This is likely due in part to the use of LHS, which typically provides fewer samples at the edges of the input space, reducing model accuracy in those regions.

**Table 4.4: Statistical Metrics of Surrogate Model Performances on Validation Data for HVAC A**

|                            | <b>MLP</b>    | <b>1<sup>st</sup> degree Polynomial</b> | <b>2<sup>nd</sup> degree Polynomial</b> | <b>3<sup>rd</sup> degree Polynomial</b> | <b>4<sup>th</sup> degree Polynomial</b> | <b>5<sup>th</sup> degree Polynomial</b> |
|----------------------------|---------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| R <sup>2</sup>             | <b>99.98%</b> | 92.89%                                  | 98.61%                                  | 99.59%                                  | <b>99.82%</b>                           | 99.66%                                  |
| MBE (kWh/m <sup>2</sup> )  | <b>-0.18</b>  | 2.30                                    | 1.60                                    | 1.23                                    | <b>0.33</b>                             | 1.17                                    |
| MAE (kWh/m <sup>2</sup> )  | <b>0.96</b>   | 18.51                                   | 7.93                                    | 4.23                                    | <b>2.88</b>                             | 3.50                                    |
| RMSE (kWh/m <sup>2</sup> ) | <b>1.18</b>   | 23.54                                   | 10.41                                   | 5.69                                    | <b>3.73</b>                             | 5.15                                    |
| NMBE                       | <b>-0.03%</b> | 0.34%                                   | 0.23%                                   | 0.18%                                   | <b>0.05%</b>                            | 0.17%                                   |
| NRMSE                      | <b>0.17%</b>  | 3.44%                                   | 1.52%                                   | 0.83%                                   | <b>0.55%</b>                            | 0.75%                                   |

**Table 4.5: Statistical Metrics of Surrogate Model Performances on Validation Data for HVAC B**

|                            | <b>MLP</b>    | <b>1<sup>st</sup> degree Polynomial</b> | <b>2<sup>nd</sup> degree Polynomial</b> | <b>3<sup>rd</sup> degree Polynomial</b> | <b>4<sup>th</sup> degree Polynomial</b> | <b>5<sup>th</sup> degree Polynomial</b> |
|----------------------------|---------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| R <sup>2</sup>             | <b>99.99%</b> | 98.50%                                  | 99.78%                                  | 99.94%                                  | <b>99.97%</b>                           | 99.89%                                  |
| MBE (kWh/m <sup>2</sup> )  | <b>-0.08</b>  | 2.33                                    | 1.24                                    | 0.57                                    | <b>0.19</b>                             | 0.45                                    |
| MAE (kWh/m <sup>2</sup> )  | <b>0.58</b>   | 10.49                                   | 3.70                                    | 2.03                                    | <b>1.29</b>                             | 2.17                                    |
| RMSE (kWh/m <sup>2</sup> ) | <b>0.83</b>   | 13.26                                   | 5.09                                    | 2.65                                    | <b>1.75</b>                             | 3.56                                    |
| NMBE                       | <b>-0.01%</b> | 0.36%                                   | 0.19%                                   | 0.09%                                   | <b>0.03%</b>                            | 0.07%                                   |
| NRMSE                      | <b>0.13%</b>  | 2.07%                                   | 0.79%                                   | 0.41%                                   | <b>0.27%</b>                            | 0.56%                                   |

**Table 4.6: Statistical Metrics of Surrogate Model Performances on Validation Data for HVAC C**

|                            | <b>MLP</b>     | <b>1<sup>st</sup> degree Polynomial</b> | <b>2<sup>nd</sup> degree Polynomial</b> | <b>3<sup>rd</sup> degree Polynomial</b> | <b>4<sup>th</sup> degree Polynomial</b> | <b>5<sup>th</sup> degree Polynomial</b> |
|----------------------------|----------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| R <sup>2</sup>             | <b>100.00%</b> | 98.91%                                  | 99.80%                                  | 99.93%                                  | <b>99.97%</b>                           | 99.91%                                  |
| MBE (kWh/m <sup>2</sup> )  | <b>0.02</b>    | 0.77                                    | 0.28                                    | -0.04                                   | <b>-0.18</b>                            | 0.10                                    |
| MAE (kWh/m <sup>2</sup> )  | <b>0.40</b>    | 7.84                                    | 3.37                                    | 1.64                                    | <b>1.28</b>                             | 1.91                                    |
| RMSE (kWh/m <sup>2</sup> ) | <b>0.53</b>    | 10.40                                   | 4.47                                    | 2.55                                    | <b>1.74</b>                             | 3.05                                    |
| NMBE                       | <b>0.00%</b>   | 0.12%                                   | 0.04%                                   | -0.01%                                  | <b>-0.03%</b>                           | 0.01%                                   |
| NRMSE                      | <b>0.08%</b>   | 1.58%                                   | 0.68%                                   | 0.39%                                   | <b>0.26%</b>                            | 0.46%                                   |

#### 4.2.4 Comparison of Surrogate Model Predictions with Numerical Model

The accuracy of the surrogate models (MLP, second-, third-, and fourth-degree polynomials), was assessed by predicting EUI for 20 randomly selected parameter value sets from the validation data, shown in Table 4.7. These EUI predictions, shown in Table 4.8, were compared against the EUI result predictions of the EnergyPlus numerical energy model for the same parameter value sets. The MLP model had a maximum error of 0.17%, the second-degree polynomial had a maximum error of 1.63%, the third-degree polynomial had a maximum error of 1.16%, and the fourth-degree polynomial had a maximum error of 0.31%. These results reinforce that the surrogate models can be effective tools for predicting EUI for high-level decision-making in retrofit projects.

**Table 4.7: 20 Random Parameter Value Sets**

| <b>Parameter Set</b> | <b>Windows<br/>(W/m<sup>2</sup>·K)</b> | <b>Walls<br/>(m<sup>2</sup>·K/W)</b> | <b>Roof<br/>(m<sup>2</sup>·K/W)</b> | <b>Infiltration<br/>(l/s· m<sup>2</sup>)</b> | <b>LPD<br/>(W/m<sup>2</sup>)</b> | <b>EPD<br/>(W/m<sup>2</sup>)</b> | <b>DHW Peak<br/>Flow Rate<br/>(l/s)</b> | <b>HVAC<br/>System</b> |
|----------------------|----------------------------------------|--------------------------------------|-------------------------------------|----------------------------------------------|----------------------------------|----------------------------------|-----------------------------------------|------------------------|
| 1                    | 0.7                                    | 4.9                                  | 9.2                                 | 0.179                                        | 8.5                              | 6.3                              | 0.0048                                  | C                      |
| 2                    | 2.0                                    | 2.5                                  | 8.5                                 | 0.541                                        | 7.5                              | 11.6                             | 0.0050                                  | A                      |
| 3                    | 1.8                                    | 4.1                                  | 2.0                                 | 0.558                                        | 12.0                             | 14.7                             | 0.0035                                  | C                      |
| 4                    | 3.1                                    | 3.8                                  | 7.6                                 | 0.257                                        | 10.7                             | 17.6                             | 0.0046                                  | B                      |
| 5                    | 2.1                                    | 6.1                                  | 10.2                                | 0.502                                        | 7.3                              | 10.0                             | 0.0050                                  | C                      |
| 6                    | 1.5                                    | 3.2                                  | 6.1                                 | 0.476                                        | 4.7                              | 8.2                              | 0.0038                                  | C                      |
| 7                    | 1.2                                    | 4.4                                  | 4.4                                 | 0.266                                        | 3.8                              | 9.3                              | 0.0036                                  | C                      |
| 8                    | 2.2                                    | 6.4                                  | 3.5                                 | 0.254                                        | 9.7                              | 5.1                              | 0.0038                                  | A                      |
| 9                    | 1.9                                    | 2.0                                  | 0.9                                 | 0.169                                        | 2.9                              | 19.7                             | 0.0034                                  | C                      |
| 10                   | 3.3                                    | 1.0                                  | 3.3                                 | 0.178                                        | 7.6                              | 5.3                              | 0.0039                                  | A                      |
| 11                   | 0.7                                    | 4.6                                  | 8.4                                 | 0.389                                        | 7.4                              | 19.6                             | 0.0043                                  | A                      |
| 12                   | 0.7                                    | 6.3                                  | 1.7                                 | 0.198                                        | 11.9                             | 14.5                             | 0.0051                                  | A                      |
| 13                   | 0.7                                    | 4.7                                  | 8.5                                 | 0.381                                        | 2.4                              | 16.1                             | 0.0035                                  | B                      |
| 14                   | 2.0                                    | 2.4                                  | 5.5                                 | 0.535                                        | 3.4                              | 12.3                             | 0.0032                                  | B                      |
| 15                   | 2.0                                    | 6.2                                  | 5.8                                 | 0.552                                        | 3.4                              | 10.4                             | 0.0041                                  | B                      |
| 16                   | 2.0                                    | 3.8                                  | 8.5                                 | 0.411                                        | 8.4                              | 14.5                             | 0.0042                                  | C                      |
| 17                   | 2.8                                    | 3.3                                  | 4.5                                 | 0.348                                        | 2.8                              | 11.5                             | 0.0041                                  | C                      |
| 18                   | 0.6                                    | 2.7                                  | 10.0                                | 0.330                                        | 8.3                              | 17.0                             | 0.0033                                  | A                      |
| 19                   | 2.5                                    | 2.4                                  | 4.6                                 | 0.167                                        | 10.2                             | 18.0                             | 0.0052                                  | B                      |
| 20                   | 3.3                                    | 2.1                                  | 8.0                                 | 0.264                                        | 9.0                              | 13.1                             | 0.0043                                  | C                      |

**Table 4.8: EUI of 20 Random Parameter Sets**

| <b>Parameter Set</b> | <b>EnergyPlus<br/>(kWh/m<sup>2</sup>)</b> | <b>MLP<br/>(kWh/m<sup>2</sup>)</b> | <b>2<sup>nd</sup> Degree<br/>Polynomial<br/>(kWh/m<sup>2</sup>)</b> | <b>3<sup>rd</sup> Degree<br/>Polynomial<br/>(kWh/m<sup>2</sup>)</b> | <b>4<sup>th</sup> Degree<br/>Polynomial<br/>(kWh/m<sup>2</sup>)</b> |
|----------------------|-------------------------------------------|------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|
| 1                    | 136.8                                     | 136.9                              | 137.0                                                               | 137.4                                                               | 136.9                                                               |
| 2                    | 217.0                                     | 216.7                              | 216.7                                                               | 218.3                                                               | 216.9                                                               |
| 3                    | 199.2                                     | 199.0                              | 200.0                                                               | 199.6                                                               | 199.5                                                               |
| 4                    | 222.5                                     | 222.6                              | 220.7                                                               | 222.4                                                               | 222.6                                                               |
| 5                    | 180.0                                     | 180.0                              | 180.3                                                               | 179.9                                                               | 179.9                                                               |
| 6                    | 156.7                                     | 156.5                              | 156.4                                                               | 156.3                                                               | 156.6                                                               |
| 7                    | 145.5                                     | 145.5                              | 146.1                                                               | 145.5                                                               | 145.9                                                               |
| 8                    | 129.5                                     | 129.4                              | 130.8                                                               | 129.3                                                               | 129.7                                                               |
| 9                    | 208.7                                     | 208.8                              | 208.6                                                               | 208.3                                                               | 208.5                                                               |
| 10                   | 170.1                                     | 170.4                              | 169.4                                                               | 170.4                                                               | 170.6                                                               |
| 11                   | 215.9                                     | 215.5                              | 213.1                                                               | 216.5                                                               | 216.0                                                               |
| 12                   | 200.6                                     | 200.8                              | 203.9                                                               | 202.9                                                               | 200.8                                                               |
| 13                   | 190.4                                     | 190.4                              | 189.4                                                               | 190.5                                                               | 190.3                                                               |
| 14                   | 172.1                                     | 172.1                              | 172.2                                                               | 171.8                                                               | 171.8                                                               |
| 15                   | 170.8                                     | 170.7                              | 169.6                                                               | 170.2                                                               | 170.7                                                               |
| 16                   | 191.4                                     | 191.5                              | 191.0                                                               | 191.4                                                               | 191.4                                                               |
| 17                   | 172.7                                     | 172.8                              | 172.7                                                               | 172.2                                                               | 172.7                                                               |
| 18                   | 186.5                                     | 186.4                              | 187.6                                                               | 185.6                                                               | 186.2                                                               |
| 19                   | 233.9                                     | 233.6                              | 232.5                                                               | 232.8                                                               | 233.5                                                               |
| 20                   | 190.1                                     | 189.9                              | 192.1                                                               | 191.3                                                               | 189.5                                                               |

#### 4.2.5 Sensitivity Analysis of Individual ECM Impacts on EUI

The MLP and the fourth-degree polynomial surrogate models were used to assess the individual impacts of each continuous ECM on the EUI. Starting from the baseline model, five incremental upgrade values were selected for each ECM (at 20% increments of each parameter range). It is important to note that the ranges used in this analysis reflect the ranges used in the sequential retrofit study (A0 to C2) and not all possible values for the ECMs.

In Figure 4.15 and Figure 4.16 it is evident that, within the bounds of this study, the infiltration had the most significant impact on EUI, while LPD and EPD had the most negligible impact. As expected, the wall and roof insulation showed diminishing returns with increased R-values. Finally, the two models produced nearly identical prediction values and patterns. While this analysis demonstrates the behaviour of the models when modifying each ECM individually, it is important to note that in a typical retrofit scenario, several ECMs would be applied concurrently.

However, the individual ECM impacts shown in this analysis cannot be added up to determine the overall EUI reduction of concurrent ECMs.

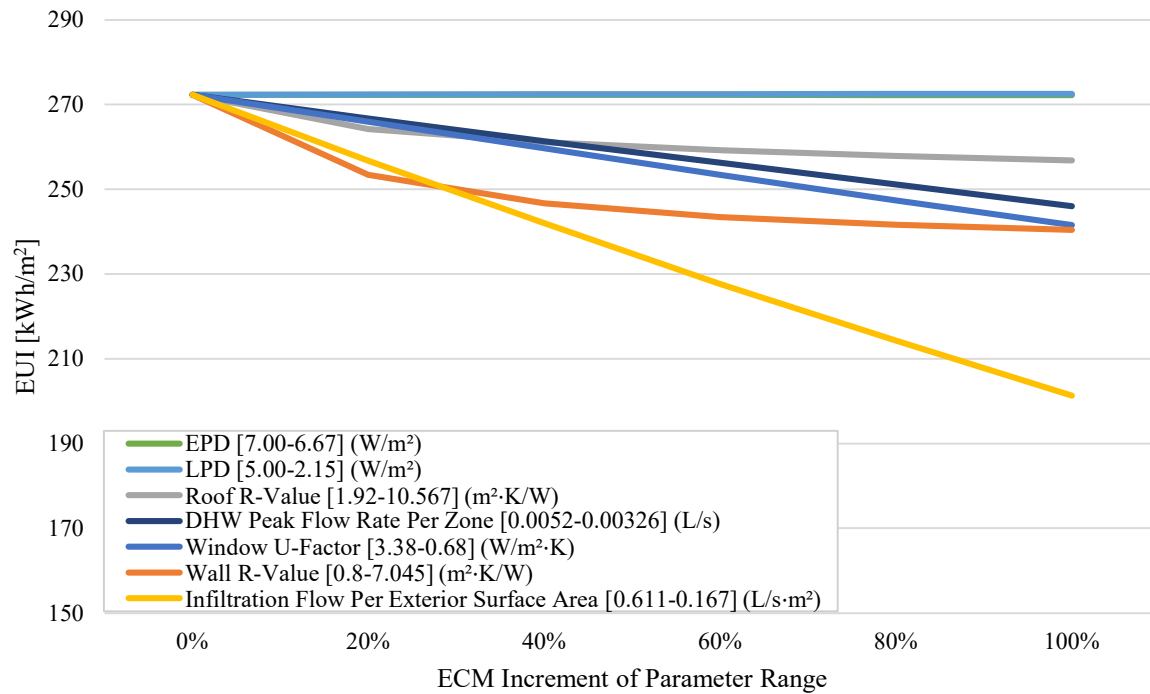


**Figure 4.15: Individual Impacts of ECMs on EUI (MLP Model)**

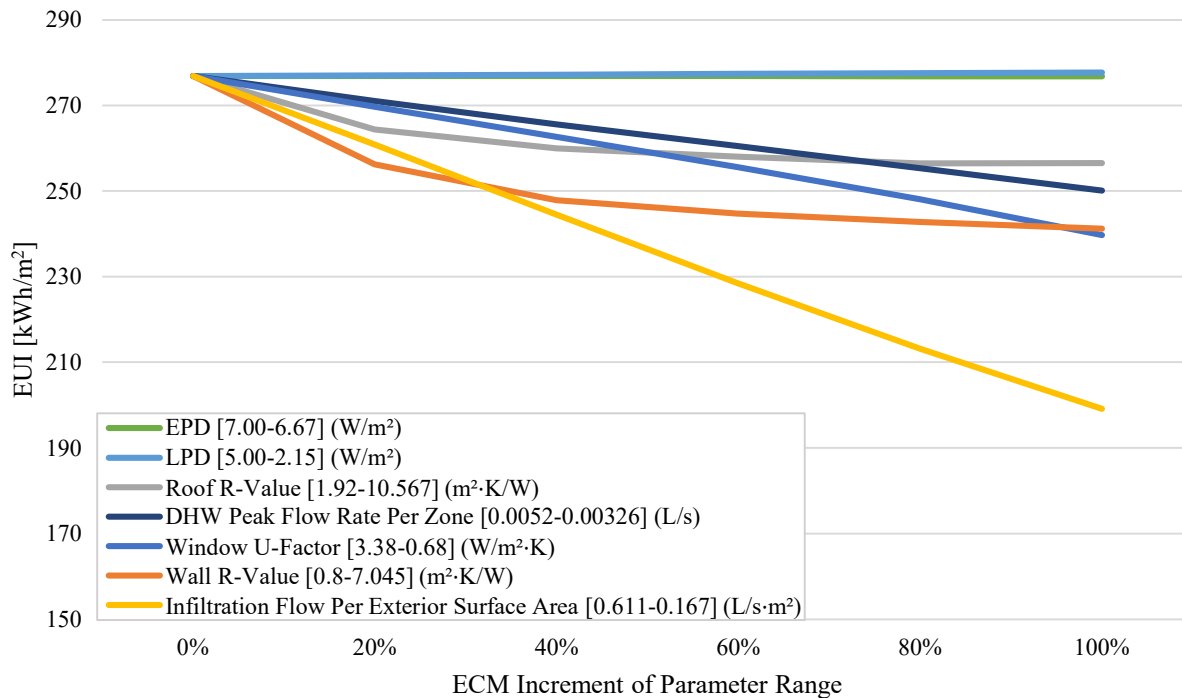


**Figure 4.16: Individual Impacts of ECMs on EUI (Fourth-Degree Polynomial Model)**

### 4.3 Sequential Retrofits Using Numerical Models

The sequential retrofits were successful at advancing energy efficiency and decarbonization; however, some of the retrofits harmed thermal stress and thermal resilience. The results for each KPI and the relationships between the KPIs studied are discussed below. The analysis was performed using the EnergyPlus numerical energy models for a mid-rise MURB in Toronto.

#### 4.3.1 Energy Efficiency

To assess the impacts of the sequential retrofits on energy efficiency, the following metrics were examined: EUI, energy consumption by end use, peak heating demand, and peak cooling demand.

The EUI of each retrofit package, along with the percent reduction in EUI relative to the baseline model (A0), is shown in Figure 4.17. The following discussion references the percentage point (pp) change relative to the previous retrofit package. The first retrofit (A1), which changed the roof colour to white (solar absorptance of 0.3 representing a thermoplastic polyolefin roof membrane), led to a 0.9 pp increase in EUI. The white roof colour resulted in reduced solar gains during the shoulder seasons (when heating is on and there is no snow on the roof), and, in turn, increased the heating demand and EUI. Although this ECM increased the EUI, it was included for its positive impact on thermal stress and thermal resilience. Additionally, it offers well-established benefits in mitigating urban heat island effects through the reduction of ambient temperatures in urban environments [92], an impact that was not evaluated under this study.

The remaining envelope retrofits were effective in reducing EUI. Upgrading the roof insulation to RSI-10.57 (A2) reduced the EUI by 6.1 pp. Next, the wall insulation was upgraded to RSI-3.52 (A3), which reduced the EUI by 10.3 pp. Further upgrading the wall insulation to RSI-7.04 (A4) only resulted in an additional 2.2 pp reduction. This indicates that both roof and wall insulation were effective ECMs for improving energy efficiency; however, there were diminishing returns when increasing the insulation level.

Next, the windows were improved. First, the windows were upgraded to a U-factor of 1.42 W/m<sup>2</sup>·K (A5), which reduced the EUI by 7.7 pp. Further upgrading the windows to a U-factor of 0.68 W/m<sup>2</sup>·K (A6) reduced the EUI by an additional 3.1 pp. Similar to insulation upgrades, window upgrades were an effective retrofit measure; however, there were diminishing returns with higher-performance windows.

The final and most effective envelope retrofit was reducing the infiltration of the MURB. Reducing the infiltration to  $0.306 \text{ L/s} \cdot \text{m}^2$  (A7) yielded a 14.6 pp reduction in EUI, and further reducing the infiltration to  $0.167 \text{ L/s} \cdot \text{m}^2$  (A8) resulted in a 3.4 pp reduction. It is important to note that, in practice, enhancing envelope airtightness should be carried out concurrently with insulation and window retrofits by adopting a continuous air barrier. However, in this sequential analysis, airtightness was evaluated as an independent ECM to isolate and better understand the individual impact of each retrofit strategy.

Following the envelope retrofits, mechanical system upgrades were implemented. First, an ASHP was added for space heating and cooling (B1). This retrofit increased the EUI by 2.4 pp due to the additional energy consumption for space cooling; however, it also significantly improved thermal stress and thermal resilience metrics (as discussed in sections 4.5.3 and 4.5.4). Next, ventilation was added in the form of an energy recovery ventilator (ERV), and the backup heating system and the DHW system were electrified (C1). The additional energy use of the ERV was offset by the improved efficiency of the electric DHW boiler, resulting in a 4.5 pp reduction in EUI. In the final retrofit step (C2), the LPD, EPD, and DHW peak flow rate were reduced to ASHRAE 90.1 levels, resulting in an 8.4 pp reduction in the EUI. The final retrofit package resulted in a 57.0% reduction in the EUI relative to the baseline model (A0). The addition of cooling and ventilation slightly increased the EUI; however, these ECMs played a crucial role in maintaining acceptable levels of thermal stress and thermal resilience. Similarly, the electrification of the HVAC and DHW systems in the MURB had a minor impact on the EUI; however, this retrofit was effective in reducing carbon emissions and supporting action towards decarbonizing the built environment.

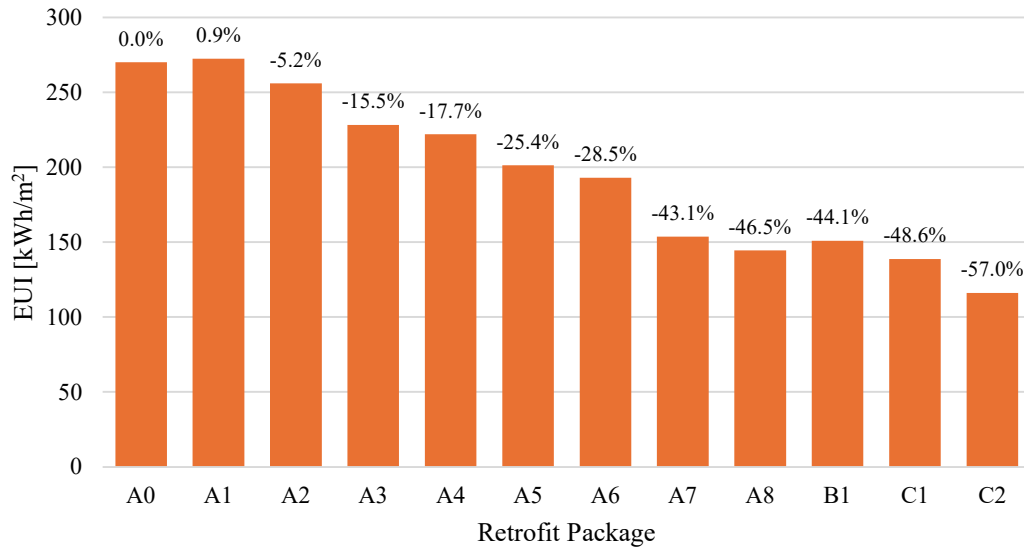


**Figure 4.17: EUI of Sequential Retrofits**

The peak heating and cooling demands for each retrofit package are shown in Figure 4.18. The peak heating demand occurred at the end of January for all retrofit packages. The envelope retrofits (A1 to A8) had a similar impact on peak heating demand as they did on EUI, resulting in a 74.9% decrease in peak heating demand compared to the baseline model (A0). As expected, when ventilation was added (C1), there was a 23.5 pp increase in peak heating demand relative to the previous step. In addition to heating the indoor air, the heating system had to compensate for the residual heat loss associated with the outdoor air introduced by the ERV, despite its sensible and latent heat recovery function. Reducing the energy consumption of the lights, equipment, and water systems (C2) had a minor impact on the peak heating demand. The final retrofit package (C2) resulted in a 53.5% decrease in peak heating demand relative to the baseline model (A0). This highlights that peak heating load reduction can be a competing objective with thermal stress and thermal resilience when adding mechanical ventilation.

In the first model with cooling (B1), the peak cooling demand occurred at the end of April, which coincided with the time when cooling was turned on. The addition of ventilation (C1) significantly reduced the peak cooling demand by 53.2% and shifted the peak to July. This indicated that, without ventilation, overheating occurred during the shoulder months preceding the activation of the cooling system. The peak cooling demand had a 1.4 pp reduction when the

plug loads were reduced to ASHRAE 90.1 levels (C2) due to the associated reduction in zone internal gains from equipment, lights, and DHW.

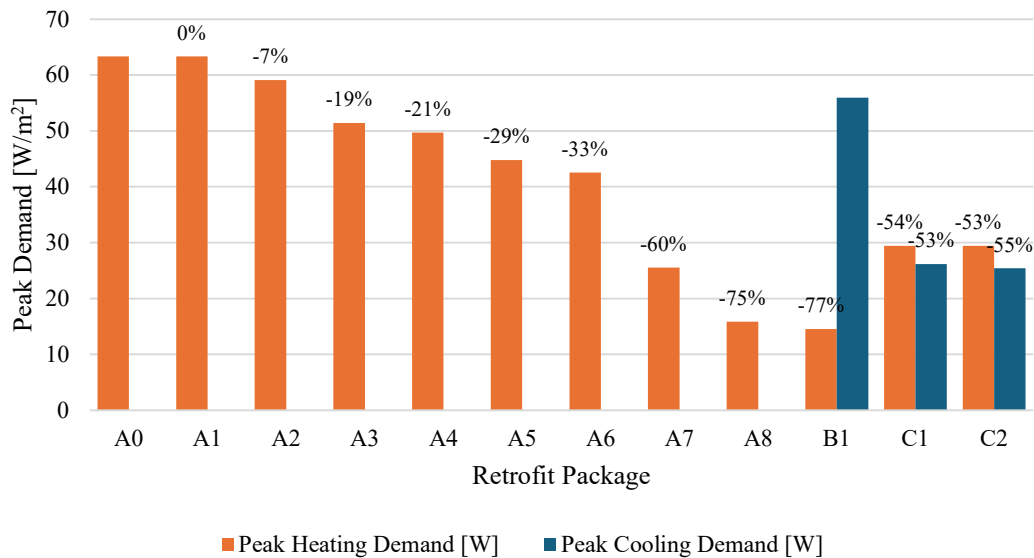


**Figure 4.18: Peak Heating and Cooling Demand of Sequential Retrofits**

EUI was then broken down by end use, as shown in Figure 4.19. Heating EUI followed similar trends to the overall EUI, as it was the largest portion of variable energy use. The envelope retrofits (A1 to A8) significantly reduced the heating EUI; however, switching from natural gas heating to an ASHP (B1) resulted in a small increase in heating EUI. This was an unexpected outcome as the natural gas heating had an efficiency of 60% and the ASHP had a rated COP of 2.5, which indicated that the ASHP should be using less energy to meet the same heating demand. Upon further investigation, it was found that the ASHP in the B1 model was running with an effective heating COP of 0.5 and that 65% of the heating EUI was attributed to the crankcase heater. A likely reason for this is that the very high-performance envelope of model B1 significantly reduced the heating demand, leading to crankcase heating dominating the total heating EUI. To confirm this theory, the ASHP retrofit was applied to the baseline model envelope (A0). In this case (A0 with ASHP), the ASHP operated with an effective COP of 1.4, and the crankcase heater only accounted for 9% of total heating EUI. Additionally, as expected, the heating EUI of this model was 59% less than that of the A0 model. Therefore, in this case, with a very high-performing envelope (B1), switching to an ASHP slightly increased the heating

EUI; however, with a more typical envelope, the ASHP was very effective in reducing the heating EUI.

The addition of ventilation in model C1 also increased heating EUI. During the winter, while the heating system was active, the ERV introduced outdoor air that was preconditioned through energy recovery. Although the incoming air was tempered, it still required supplemental heating to reach indoor setpoints. In contrast, cooling EUI decreased with the addition of ventilation (C1). In the summer, the ERV helped reduce the cooling load by introducing cooler night-time air, which was also preconditioned through energy recovery, thereby lowering the demand on the mechanical cooling system.

The water system's EUI was reduced when switching to an electric (non-condensing) boiler (C1), and it was further reduced when usage was lowered to ASHRAE 90.1 levels (C2). The EUI of lights and equipment remained constant throughout all the retrofit packages, except for the final package, where their usage was reduced to ASHRAE 90.1 levels (C2).

In the baseline model (A0), space conditioning loads accounted for 56% (150.89 kWh/m<sup>2</sup>) of the total EUI, while base loads (lights, equipment, and water systems) accounted for the remaining 44% (119.07 kWh/m<sup>2</sup>). In the final retrofit model (C2), space conditioning loads accounted for only 33% of the total EUI (38.23 kWh/m<sup>2</sup>), while base loads accounted for the remaining 67% (77.94 kWh/m<sup>2</sup>). The ECM strategies influenced not only the EUI but also altered the energy signature of the mid-rise MURB by shifting a portion of the energy demand from heating to base loads. In the case of a well-insulated, airtight, fully electrified mid-rise MURB (C2), end uses that are highly dependent on occupant behavior, such as lighting, plug loads, and DHW, account for approximately two-thirds of the total energy consumption. Although this study employed standard occupancy schedules and internal loads based on ASHRAE 90.1, a sensitivity analysis on occupant behavior could provide valuable insights into the level of model uncertainty introduced by user-driven variability.

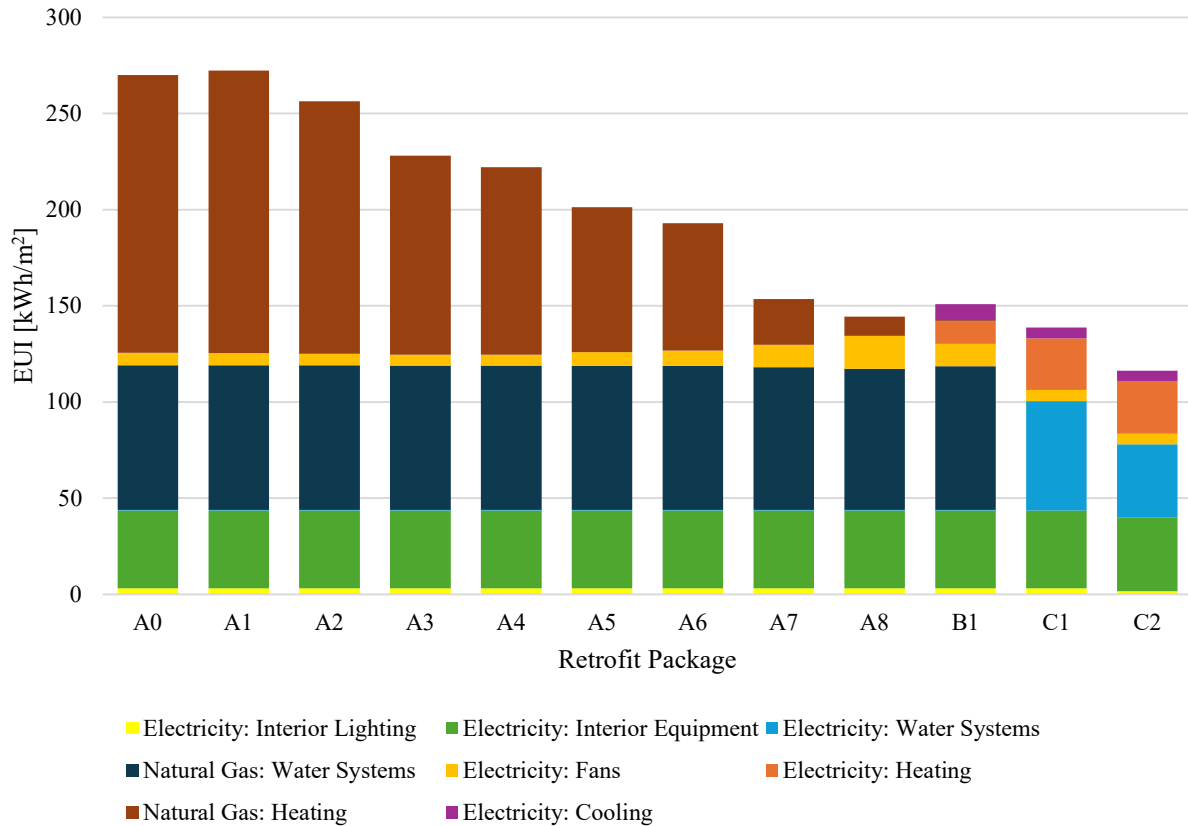


**Figure 4.19: Energy Use by End Use of Sequential Retrofits**

#### 4.3.2 Decarbonization

Greenhouse gas emissions factors for natural gas and electricity from the 2022 National Inventory Report [93] were included in the Energy Plus model to estimate the annual operational carbon emissions. The first set of retrofit packages (A1 to A8) focused on building envelope retrofits. Since there were no changes to fuel sources in these packages, the carbon emissions followed similar trends to the EUI, as shown in Figure 4.20. When all the envelope ECMs were implemented (A8), it resulted in a 58.3% reduction in operational carbon emissions.

In 2021, 91% of Ontario's electricity was generated from zero-carbon sources, including nuclear, hydro, wind, and solar energy. Only 8% of electricity generation used natural gas [94]; therefore, the electrical grid has lower carbon emissions than natural gas. Retrofit package B1 utilized an electric ASHP for space heating and cooling, instead of natural gas. Even with the addition of space cooling, electrifying the primary space heating system resulted in a slight reduction in carbon emissions. The C1 retrofit package was fully electrified, resulting in an 87.7% reduction

in carbon emissions compared to the baseline scenario (A0). This reduction is more significant than the EUI reduction achieved by the C1 retrofit package (48.6%), indicating that the main benefit of electrification is the reduction of carbon emissions. By retrofitting the lighting, equipment, and DHW in package C2, an 89.7% reduction was achieved relative to the baseline scenario (A0). These results clearly show that electrification is the most important retrofit for reducing carbon emissions.

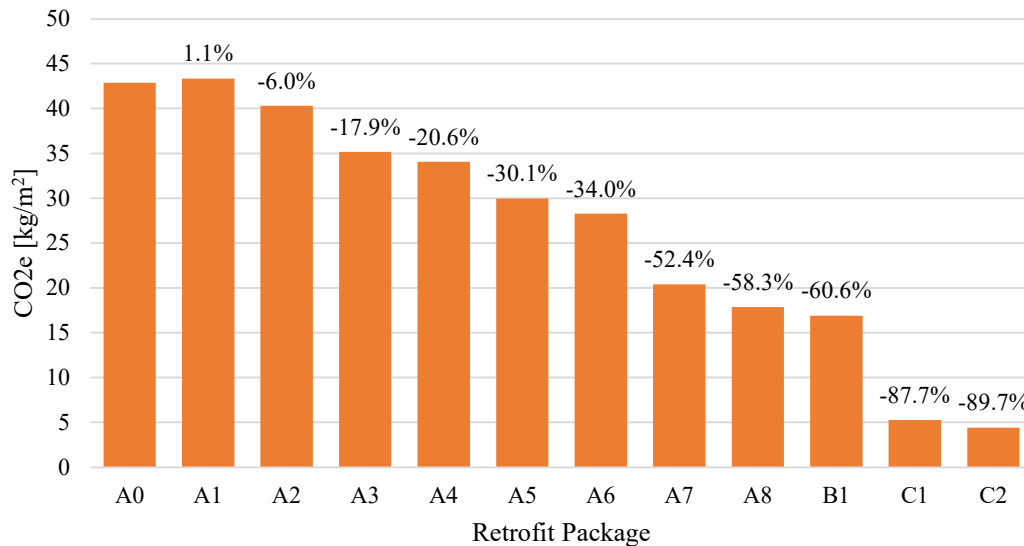


**Figure 4.20: Operational Carbon Emissions of Sequential Retrofits**

### 4.3.3 Thermal Stress

The sequential retrofits were chosen primarily to reduce EUI and carbon emissions; however, these retrofits can also affect the thermal stress experienced by occupants of the MURB. While the baseline model and all retrofit packages performed well during the heating season, many simulations indicated poor performance during the cooling season due to the lack of space cooling and ventilation. When retrofit strategies are evaluated solely on EUI and emissions, without considering occupant comfort, they can result in a significant increase in overheating degree-hours. This poses serious risks to occupant health and well-being, especially for vulnerable groups such as children and the elderly [95]. To assess the impact of the retrofits on thermal stress, humidex hours, and SET degree-hours were analyzed. It is essential to note that this study employed a worst-case scenario, in which natural ventilation (e.g., window opening) was unavailable to occupants of the MURBs. The results could potentially improve with the

implementation of natural ventilation strategies (e.g., night cooling, when outdoor temperatures and humidity levels are favorable). However, because such strategies depend heavily on occupant behavior and are difficult to standardize, they were excluded from this analysis.

*Humidex is an index number used by Canadian meteorologists to describe how hot the weather feels to the average person, by combining the effects of heat and humidity [85].* The humidex hours for five levels (1. little to no discomfort, 2. some discomfort, 3. great discomfort, avoid exertion, 4. dangerous, and 5. heat stroke imminent) for the entire year are shown in Figure 4.21 below. The first retrofit, changing the roof colour to white (A1), resulted in a 1.2 pp increase in humidex comfortable hours. The remaining envelope retrofits (A2 to A8) were detrimental to thermal stress, with retrofit package A8 resulting in a 54.4% decrease in humidex hours compared to the baseline model (A0). The improved airtightness (A7) was the most detrimental to humidex comfortable hours, followed by window improvements (A5), wall insulation upgrades (A3), and roof insulation upgrades (A2).

While the envelope retrofits significantly reduced the number of comfortable humidex hours, the mechanical system retrofits effectively improved the thermal stress metrics. In retrofit package B1, the addition of cooling increased the comfortable humidex hours by 63.7 pp relative to the previous step. This retrofit mitigated most of the overheating experienced throughout the year; however, the cooling system was scheduled to operate only from May 1st to October 31st, leading to periods during the shoulder seasons with uncomfortable humidex hours. In package C1, adding ventilation increased the comfortable humidex hours by an additional 19.0 pp. The ventilation was active throughout the entire year, addressing uncomfortable hours experienced during the shoulder seasons. These results demonstrate that space cooling and ventilation are crucial for mitigating thermal stress in MURBs with high-performance envelopes.

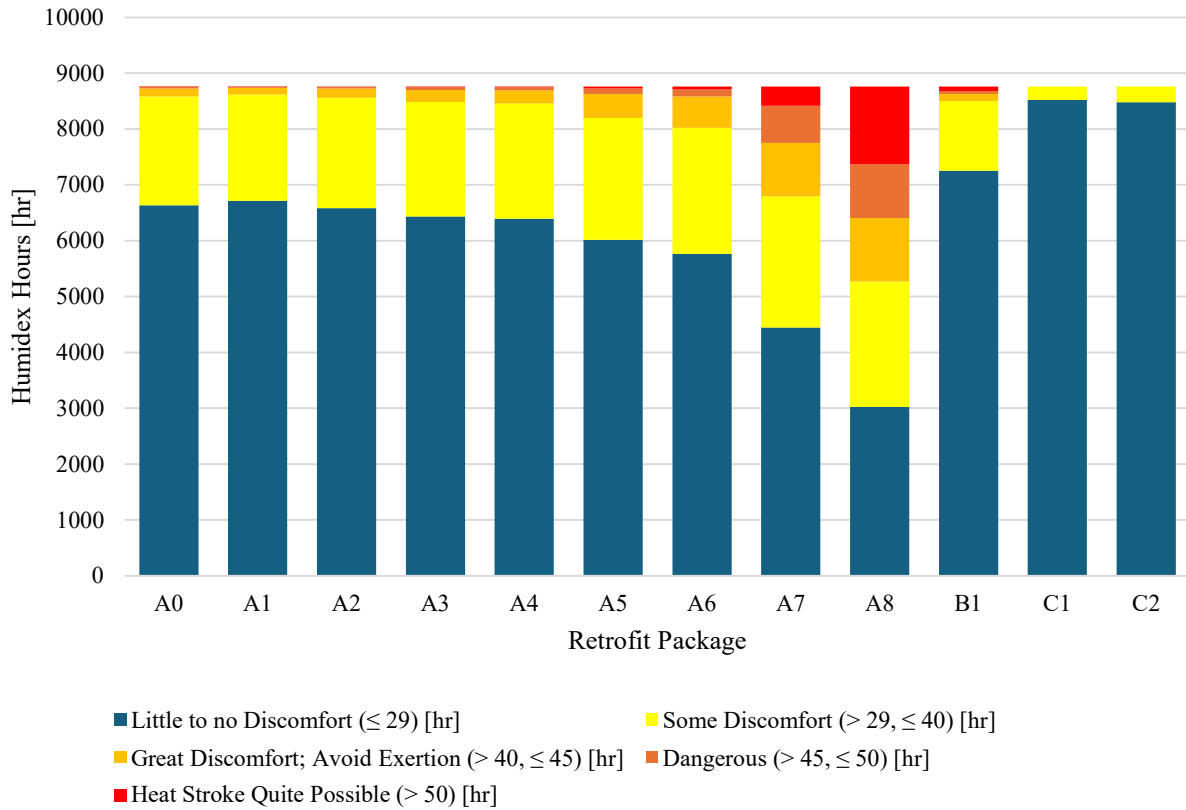


**Figure 4.21: Humidex Hours of Sequential Retrofits**

*SET is a comprehensive comfort index based on heat-balance equations that incorporate personal factors, such as clothing and metabolic rate [85].* The cooling SET >30°C degree-hours for an entire year for all the retrofit packages are shown in Figure 4.22 below. The cooling SET measures both the magnitude and duration of cooling events where the SET exceeds 30°C. The baseline model (A0) had 394°C·hr cooling SET. Changing the roof colour to white (A1) was an effective measure for improving thermal stress, and it reduced the cooling SET to 280°C·hr. Improvements to the roof and wall insulation increased the cooling SET, but still maintained it below 1,000°C·hr. Similar to the humidex hours, window improvements and airtightness upgrades had a larger impact on the cooling SET. Improving the window U-factor (A6) increased the cooling SET to 3,674°C·hr, and reducing infiltration (A8) further increased it to 30,393°C·hr. Adding cooling to the MURB reduced the cooling SET to 4,154°C·hr. Finally, adding ventilation reduced the cooling SET to 0°C·hr, eliminating overheating events. These results clearly show that high-performance envelopes significantly increase the risk of overheating, underscoring the importance of including cooling and ventilation systems to maintain occupant comfort.

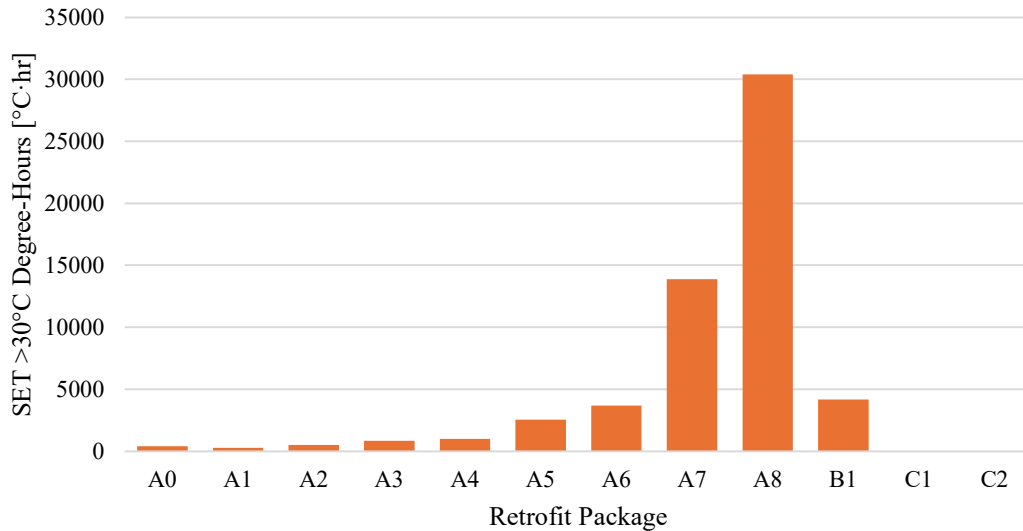


**Figure 4.22: Cooling SET Degree-Hours of Sequential Retrofits**

#### 4.3.4 Thermal Resilience

Similar to thermal stress, the thermal resilience of the MURB was negatively impacted by many of the retrofits. To evaluate thermal resilience, the hours of safety for cold and heat events were analyzed. The cold stress temperature threshold for cold events was 16°C, and the heat stress temperature threshold for heat events was 30°C [85]. As all retrofit packages included space heating systems, they all achieved the maximum (8760 hours) hours of safety for cold events. The hours of safety for heat events for an entire year for all the retrofit packages are shown in Figure 4.23 below. The baseline model (A0) maintained safe temperatures for 95% of the year, and the addition of all the envelope retrofits (A8) resulted in safe temperatures for only 40% of the year. The addition of space cooling (B1) increased the hours of safety to 84% of the year; however, overheating still occurred during the shoulder seasons. Finally, the addition of ventilation (C1) ensured safe temperatures throughout the entire year, as the ventilation remained active year-round. The original MURB was not capable of maintaining safe temperatures during heat events, and the envelope upgrades exacerbated this issue, particularly when increasing the airtightness of the building. The space cooling and ventilation systems were effective retrofits, ensuring that safe temperatures were maintained throughout the year. From these findings, it is evident that envelope retrofits focused solely on reducing energy use can have a significant adverse effect on the thermal resilience of MURBs when no natural ventilation strategies are implemented.

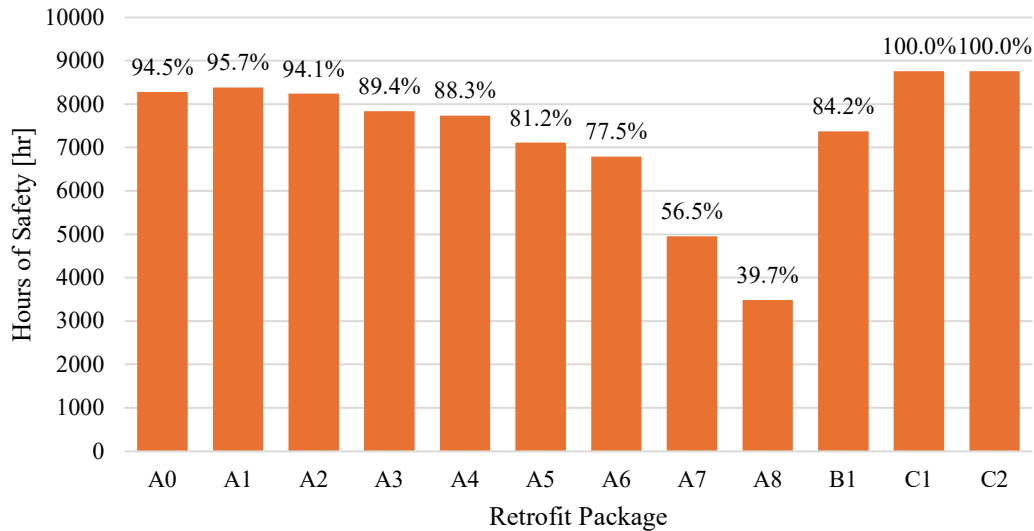


**Figure 4.23: Hours of Safety for Heat Events of Sequential Retrofits**

#### 4.4 Comparison of Surrogate Model and Numerical Model Retrofit Predictions

In the previous section, EnergyPlus was used for the sequential retrofit analysis because it involved analyzing several KPIs, and the surrogate models were only designed to predict EUI. However, to further demonstrate the effectiveness of the surrogate models in assessing retrofit packages, they were used to predict the EUI of each sequential retrofit package. Then, these predictions were compared to the EnergyPlus results from the sequential retrofit analysis, as shown in Table 4.9. For all the sequential retrofit packages, the predictions using the MLP surrogate model were within 1.2% of the EnergyPlus results, and the predictions using the fourth-degree polynomial equation were within 1.7%.

**Table 4.9: Comparison of EnergyPlus vs Surrogate Model for EUI Predictions for Sequential Retrofit Analysis**

| <b>Sequential Retrofit Package</b> | <b>EnergyPlus (kWh/m<sup>2</sup>)</b> | <b>MLP (kWh/m<sup>2</sup>) (MBE)</b> | <b>2<sup>nd</sup> Degree Polynomial (kWh/m<sup>2</sup>)</b> | <b>3<sup>rd</sup> Degree Polynomial (kWh/m<sup>2</sup>)</b> | <b>4<sup>th</sup> Degree Polynomial (kWh/m<sup>2</sup>)</b> |
|------------------------------------|---------------------------------------|--------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| A0                                 | 269.96                                | 272.27<br>(-0.86%)                   | 275.99<br>(-2.23%)                                          | 273.86<br>(-1.44%)                                          | 274.49<br>(-1.68%)                                          |
| A2                                 | 255.94                                | 256.82<br>(-0.34%)                   | 258.61<br>(-1.04%)                                          | 265.24<br>(-3.63%)                                          | 254.39<br>(0.61%)                                           |
| A3                                 | 228.08                                | 228.35<br>(-0.12%)                   | 236.86<br>(-3.85%)                                          | 235.05<br>(-3.06%)                                          | 226.80<br>(0.56%)                                           |
| A4                                 | 222.05                                | 222.05<br>(0.00%)                    | 227.28<br>(-2.36%)                                          | 227.91<br>(-2.64%)                                          | 221.29<br>(0.34%)                                           |
| A5                                 | 201.31                                | 201.68<br>(-0.18%)                   | 205.47<br>(-2.07%)                                          | 202.59<br>(-0.64%)                                          | 202.57<br>(-0.63%)                                          |
| A6                                 | 192.97                                | 194.47<br>(-0.78%)                   | 198.14<br>(-2.68%)                                          | 192.80<br>(0.09%)                                           | 193.05<br>(-0.04%)                                          |
| A7                                 | 153.58                                | 155.39<br>(-1.18%)                   | 162.38<br>(-5.73%)                                          | 153.11<br>(0.31%)                                           | 155.85<br>(-1.48%)                                          |
| A8                                 | 144.38                                | 145.24<br>(-0.60%)                   | 151.76<br>(-5.11%)                                          | 140.13<br>(2.94%)                                           | 143.58<br>(0.55%)                                           |
| B1                                 | 150.86                                | 151.94<br>(-0.72%)                   | 154.14<br>(-2.17%)                                          | 149.81<br>(0.70%)                                           | 149.88<br>(0.65%)                                           |
| C1                                 | 138.71                                | 139.74<br>(-0.74%)                   | 142.26<br>(-2.56%)                                          | 139.84<br>(-0.81%)                                          | 139.28<br>(-0.41%)                                          |
| C2                                 | 116.17                                | 116.88<br>(-0.61%)                   | 119.24<br>(-2.64%)                                          | 116.85<br>(-0.59%)                                          | 117.29<br>(-0.96%)                                          |

Additionally, Figure 4.24 shows that all the surrogate models reproduce the Energy Plus results across the different retrofit packages, with close agreement in direction and relative magnitude. This agreement further supports their use for high-level decision-making and comparative evaluation of retrofit options.

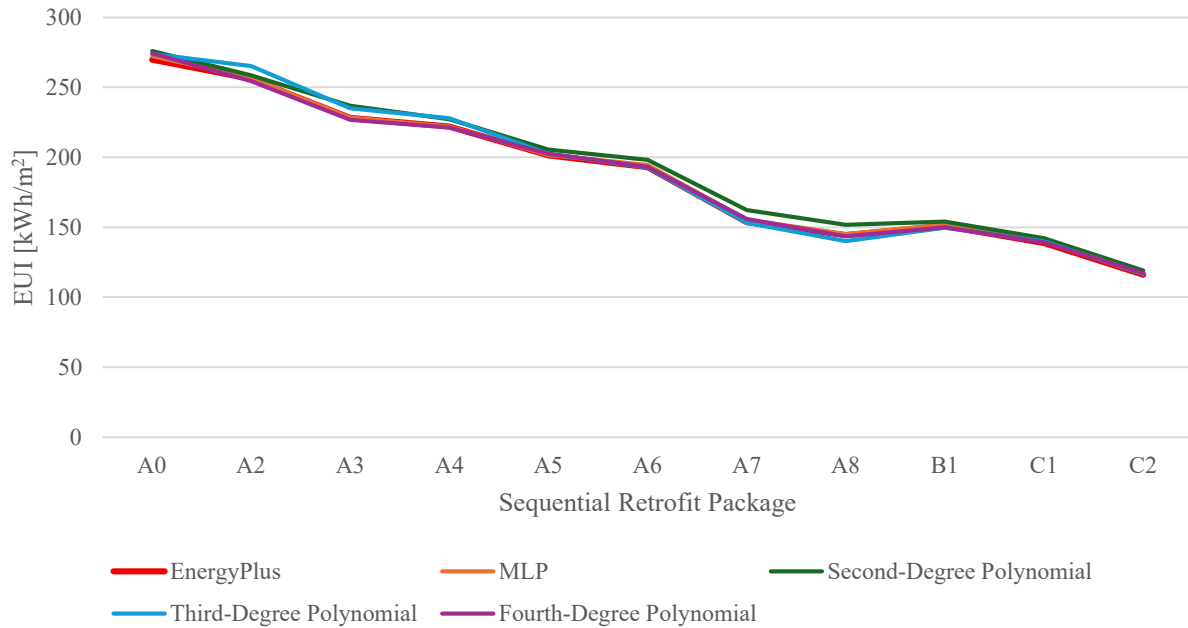


**Figure 4.24: EUI Comparison of Surrogate Model and Numerical Model Predictions for Sequential Retrofit Packages**

## 4.5 Future Climate Results

The sequential retrofits were also evaluated under future climate conditions using a 3.5°C global warming scenario. This was the most extreme global warming weather file available from the National Research Council [91]; therefore, any global warming scenario between current temperatures and 3.5°C of warming would fall within the bounds of the results of this study. The main differences in the 3.5°C global warming scenario were an increase in average outdoor air temperature and an increase in relative humidity. It was expected that these changes would lead to a reduction in thermal energy demand intensity (TEDI), an increase in cooling energy demand intensity (CEDI), a decrease in comfortable humidex hours, and a decrease in hours of safety.

### 4.5.1 HVAC Sizing Comparison

The design day conditions were updated in EnergyPlus to represent the 3.5°C global warming scenario for 99.6% annual exceedance probabilities based on ASHRAE Handbook – Fundamentals [96]. The design day is used to size the HVAC equipment; therefore, the HVAC sizing is different between the current and future climate files. The user design load per area was analyzed under both heating and cooling conditions.

The heating user design load is lower for future climate conditions than for current climate conditions for each retrofit package, as shown in Figure 4.25. The building envelope ECMs, excluding the final infiltration upgrade (A1 to A7), demonstrate that the heating user design load decreased by 17% to 21% under future climate conditions. Higher outdoor air temperatures led to a reduced heating demand. The final infiltration upgrade (A8) resulted in a highly insulated building envelope with minimal air leakage, which meant that the outdoor temperature had a less significant impact on the building's energy demand. The results for packages A8 to C2 show only minor differences between current climate and future climate conditions.

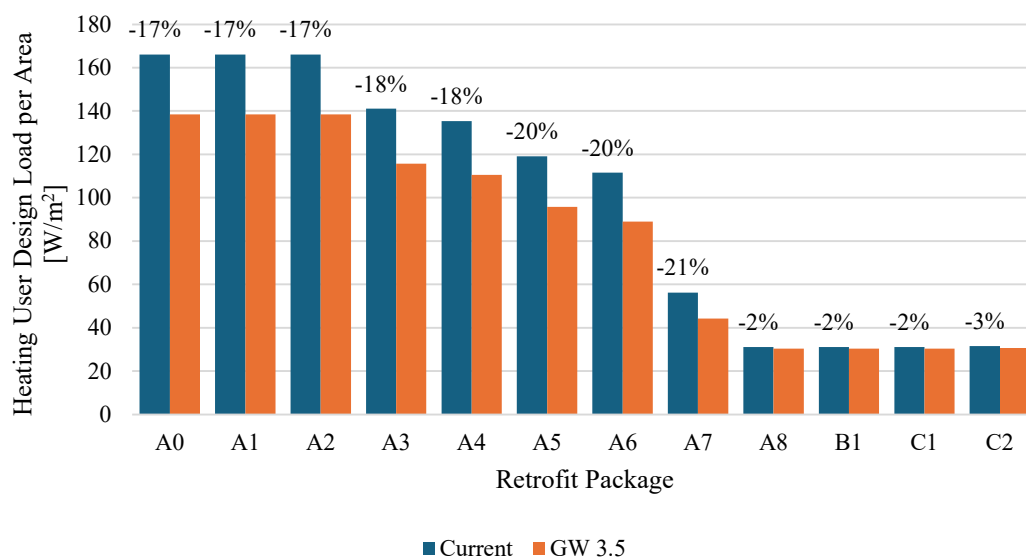


**Figure 4.25 Heating User Design Load per Area Under Current and Future Climate Conditions**

The cooling user design load is higher under future climate conditions than current climate conditions for each retrofit package, as shown in Figure 4.26. The difference between current and future climate conditions was reduced as the building envelope was improved (A1 to A8). Similar to the heating user design load, the improved building envelope effectively mitigated the effects of the future climate conditions on the cooling user design load. The results for packages A8 to C2 show a slight difference in the cooling user design load between current and future climate conditions.

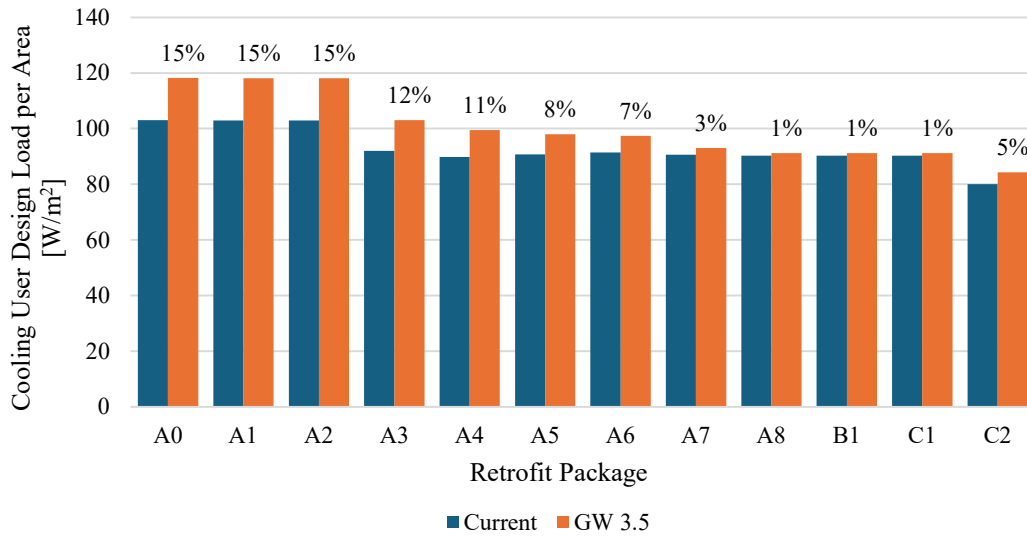


**Figure 4.26 Cooling User Design Load per Area Under Current and Future Climate Conditions**

#### 4.5.2 Energy Efficiency

When switching to future climate conditions, the EUI decreased for most retrofit packages. Under current climate conditions, heating EUI accounted for a significant portion of the total EUI, and when switching to the future climate conditions, the heating demand was reduced significantly. Figure 4.27 shows that as envelope performance was improved (A0 to A8), the difference between current and future climate results decreased. Under current climate conditions, the envelope retrofits substantially reduced the heating EUI; however, with the reduced heating demand under future conditions, the impact of the envelope upgrades on reducing EUI was also diminished. When an ASHP was added (B1), there was almost no change to the EUI between current and future conditions, as the increased outdoor air temperature both reduced the heating demand and increased the cooling demand. With the addition of ventilation (C1 and C2), the EUI decreased slightly (4.1% to 5.3%) under future climate conditions, as the decrease in heating energy use was greater than the increase in cooling energy use.

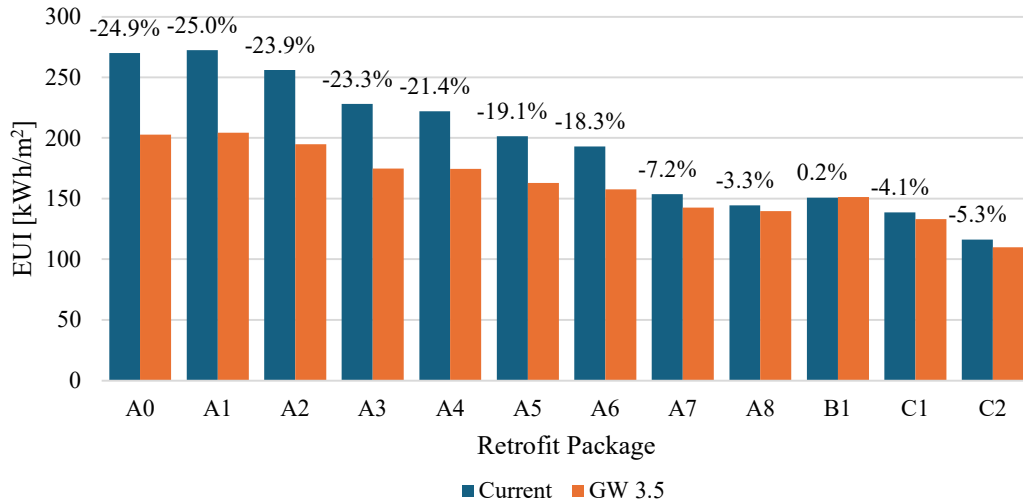


**Figure 4.27: EUI Under Current and Future Climate Conditions**

Space heating and space cooling were the energy end uses primarily impacted by climate conditions; therefore, TEDI, peak heating demand, CEDI, and peak cooling demand were examined under the 3.5°C global warming scenario. As expected, the TEDI of the MURB decreased significantly across all retrofit packages, with reductions ranging from 48.1% to 67.9%, as shown in Figure 4.28. The trends between the different retrofit packages were similar under the current and future climate conditions.

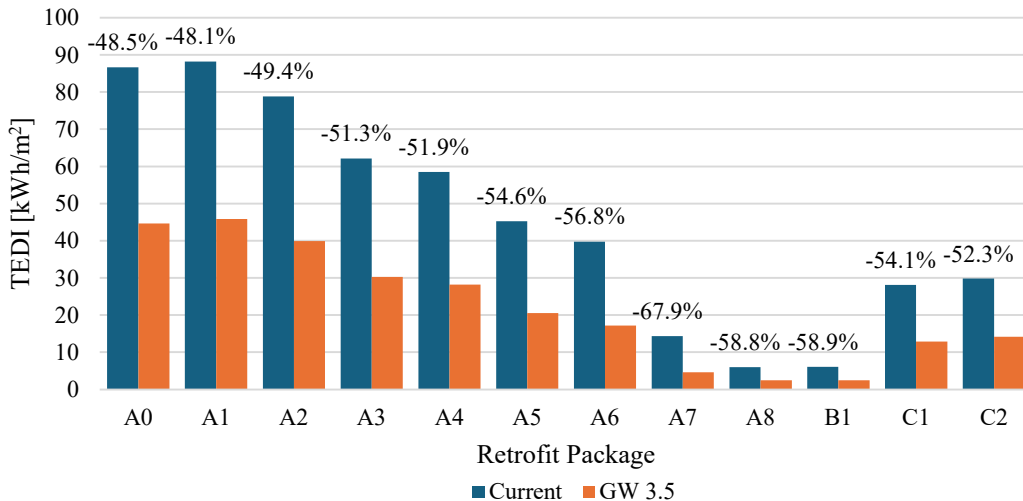


**Figure 4.28: TEDI Under Current and Future Climate Conditions**

Similar trends were observed for peak heating demand, as shown in Figure 4.29. The peak heating demand decreased between 32.2% and 50.4% under future climate conditions. The peak heating demand trends between retrofit packages were also similar between current and future

climate conditions. Note that the peak heating demand for the year, as observed in Figure 4.29, is not identical to the design heating load presented in Figure 4.25 due to fundamental differences in how each is determined. The annual peak heating demand reflects the highest instantaneous heating requirement based on dynamic hourly conditions throughout the year. It accounts for actual internal gains, solar radiation, occupancy, ventilation rates, and weather fluctuations. In contrast, the design heating load in Figure 4.25 is based on a static design day calculation using standardized assumptions, such as the 99.6% winter design temperature, with minimal or no contribution from internal and solar gains. The latter method is intended for conservative HVAC sizing rather than capturing real-world variability. As a result, the design heating load is often higher than the simulated peak demand, reflecting a safety margin rather than an actual observed condition.

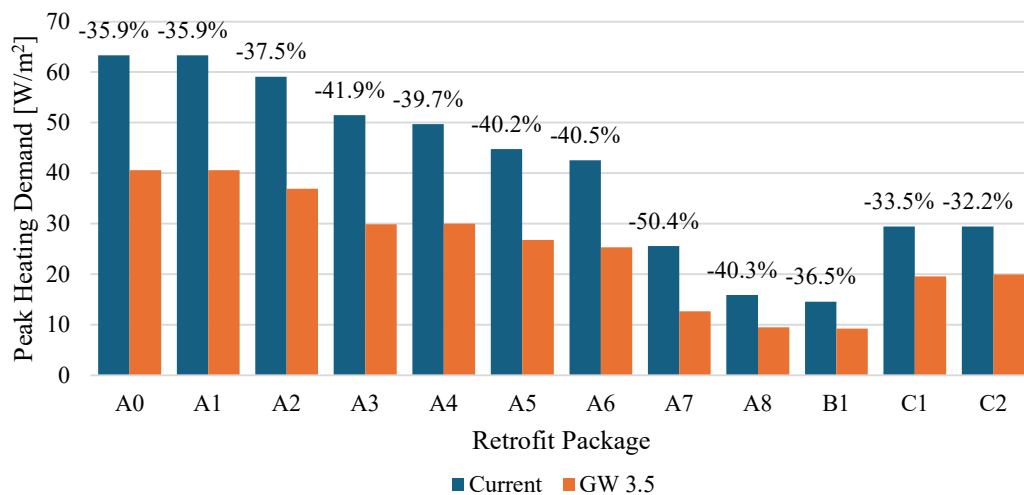


**Figure 4.29: Peak Heating Demand Under Current and Future Climate Conditions**

The CEDI of the MURB increased significantly in the future climate scenario, ranging from a 38.3% increase to a 114.2% increase, as shown in Figure 4.30. Under current climate conditions, adding ventilation (C1 and C2) significantly reduced the CEDI; however, under future conditions, it had a minimal impact. Future climate conditions have increased outdoor air temperatures and relative humidity throughout the cooling season, resulting in higher latent cooling loads as more energy is required for dehumidification to maintain indoor comfort conditions.

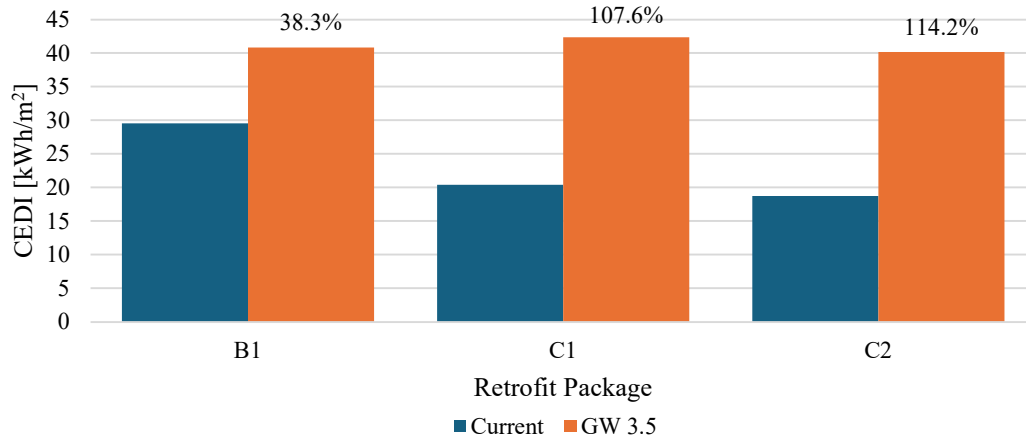


**Figure 4.30: CEDI Under Current and Future Climate Conditions**

Similarly, the peak cooling demand increased between 15.7% and 125.2% as shown in Figure 4.31. Under current climate conditions, adding ventilation (C1 and C2) significantly decreased the peak cooling demand; however, this retrofit was less effective under future conditions due to the higher latent cooling loads.

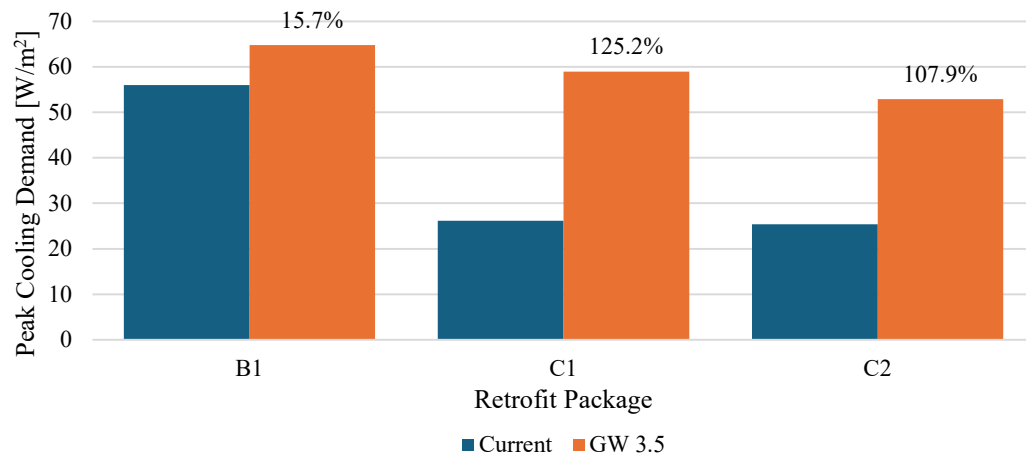


**Figure 4.31: Peak Cooling Demand Under Current and Future Climate Conditions**

### 4.5.3 Thermal Stress

The humidex hours of the sequential retrofits under future climate conditions (Figure 4.32) followed similar trends to those under current climate conditions (Figure 4.21). All retrofit packages experienced a shift to more uncomfortable humidex hours under future climate conditions, primarily due to increased outdoor air temperatures. For the baseline model (A0) and the insulation and window retrofit packages (A2 to A6), switching to future climate conditions

resulted in a 23% to 25% reduction in the number of comfortable humidex hours. For the infiltration retrofit packages (A7 and A8), switching to future climate conditions reduced the humidex comfortable hours by 29% and 47%, respectively. Package A8 under future climate conditions only maintained comfortable conditions for 18.3% of the year. This indicated that improved airtightness without space cooling and ventilation significantly increased thermal stress under future climate conditions. For retrofit package B1, which included cooling, switching to future climate conditions reduced the number of comfortable humidex hours by 18%. For retrofit packages C1 and C2, which included ventilation, switching to future climate conditions reduced the number of comfortable humidex hours by 10% to 11%. However, package C2 still maintained comfortable conditions for 86.9% of the year and kept conditions below dangerous levels for the entire year. This indicated that these mechanical system upgrades were still effective measures for maintaining occupant thermal comfort under future climate conditions.

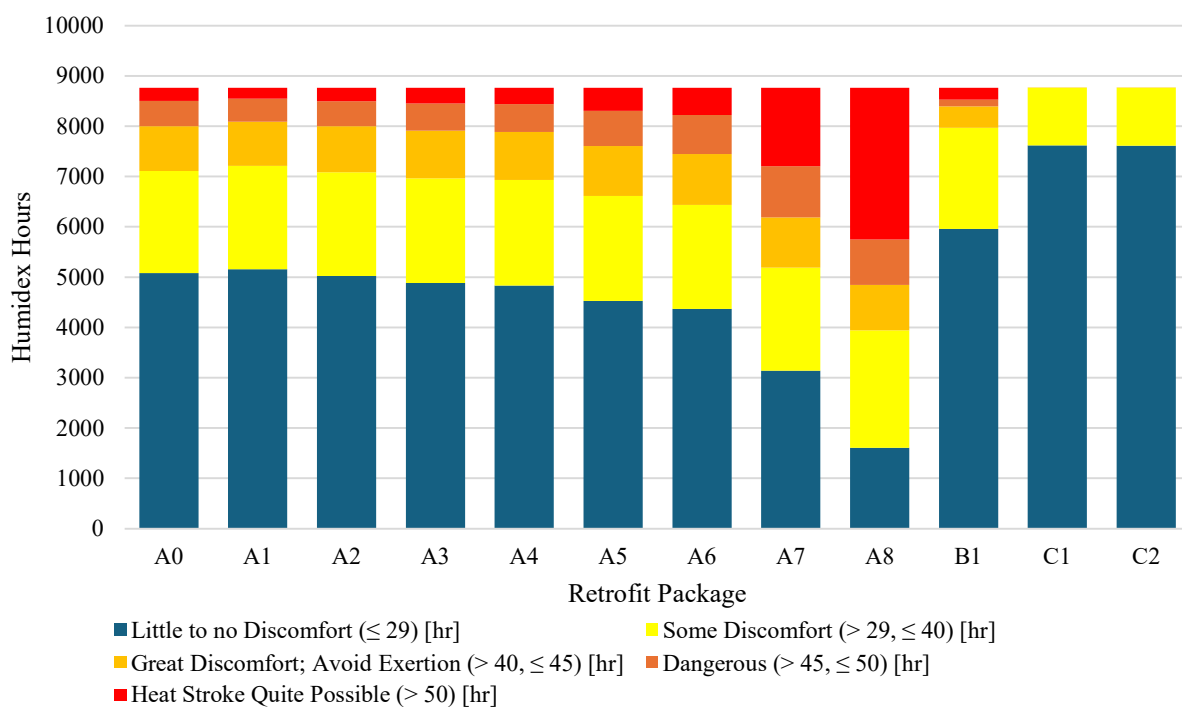


**Figure 4.32: Humidex Hours Under Future Climate Conditions**

The cooling SET degree-hours increased significantly under future climate conditions; however, the retrofit packages with both cooling and ventilation (C1 and C2) were able to achieve very low SET degree-hours (25.77°C·hr). The trends between the different retrofit packages for current and future climate conditions are very similar, as shown in Figure 4.33

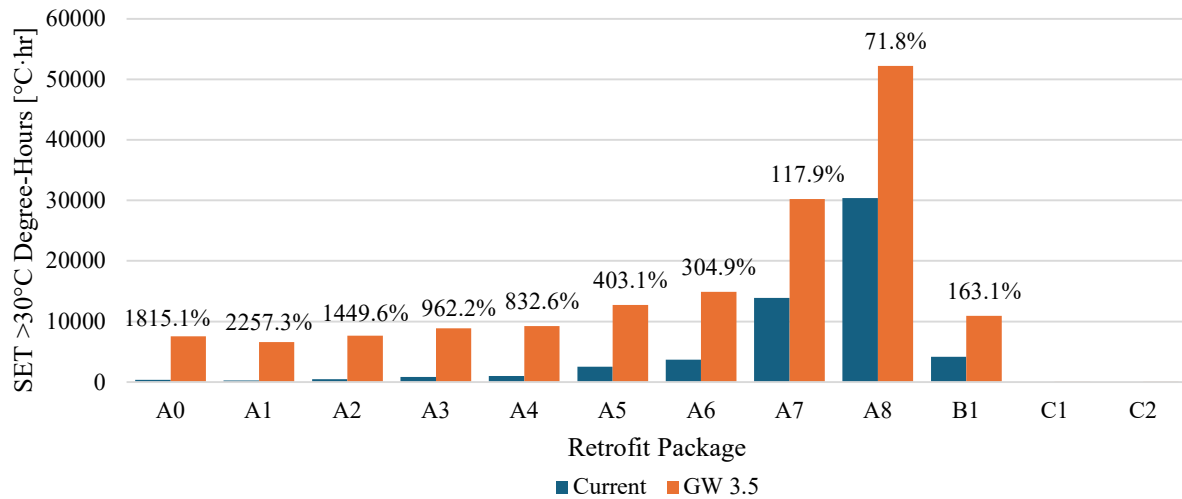


**Figure 4.33: Cooling SET Under Current and Future Climate Conditions**

#### 4.5.4 Thermal Resilience

Under future climate conditions, the MURB was still able to maintain safe temperatures for cold events throughout the entire year. For heat events, the hours of safety followed similar trends as under current climate conditions. However, under future climate conditions, the hours of safety were reduced, as shown in Figure 4.34. This was expected, as under future climate conditions, heat events were expected to be more extreme in both frequency and intensity. The decrease in hours of safety from current to future conditions remained relatively constant (23.5% to 25.5%) across the first envelope retrofits (A1 to A6); however, a more significant decrease was observed when reducing infiltration (A8). This indicated that an airtight envelope without space cooling or ventilation became an even larger hazard to occupant safety under future conditions. Package B1 with cooling saw a smaller decrease (16.5%) when transitioning to future climate conditions. Packages C1 and C2 with ventilation were able to maintain safe conditions throughout the year, even under future climate conditions.

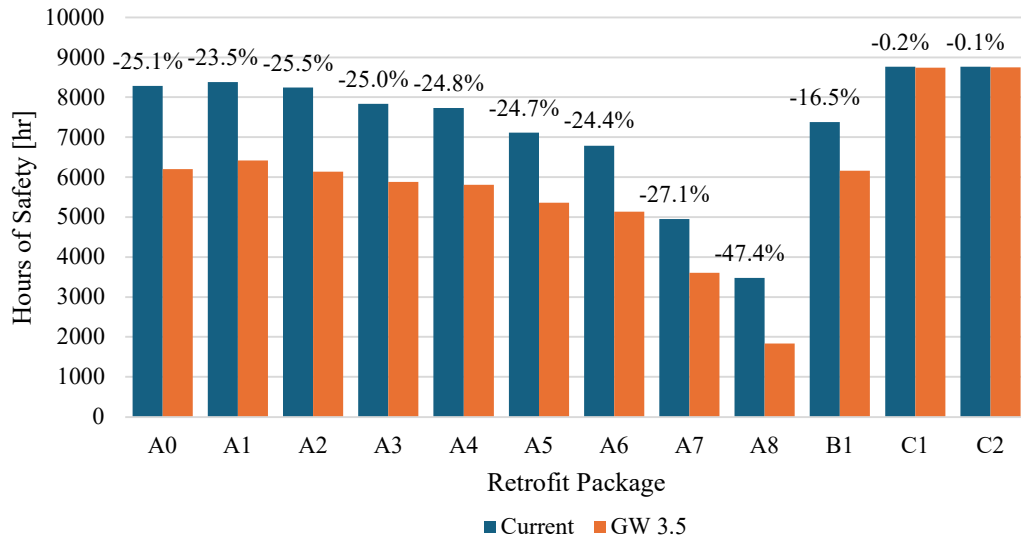


**Figure 4.34: Hours of Safety for Heat Events Under Current and Future Climate Conditions**

## 5 Summary and Conclusions

For Canada to achieve its decarbonization goals, a significant increase in the number of building retrofit projects will be required. This study implemented common ECMs in MURB retrofit projects and assessed their impacts on energy efficiency, decarbonization, thermal stress, and thermal resilience. The results of this study highlighted the importance of broadening the scope of retrofit projects beyond energy efficiency and carbon emission reductions to ensure safety and comfort for occupants.

A significant contribution of this work was the development of predictive surrogate models that can predict EUI for various ECM values for mid-rise MURBS in the City of Toronto. The MLP surrogate models had the highest accuracy ( $R^2$  values  $>99.98\%$  and RMSE of  $<1.18$  kWh/m<sup>2</sup>/year); however, the fourth-degree polynomial models were also very accurate ( $R^2$  values  $>99.82\%$  and RMSE of  $<3.73$  kWh/m<sup>2</sup>/year). The fourth-degree polynomial equation can be easily used to predict the EUI of similar MURBs by entering ECM values into the equation.

The results of the sequential retrofit analysis showed that while energy efficiency should be prioritized in retrofits, a more holistic approach is necessary to account for the thermal stress and thermal resilience of the building. Focusing only on envelope retrofits reduced EUI by 47% but also reduced the hours of safety during heat events by 53% and the humidex comfortable hours by 54%. Adding cooling and ventilation increased the energy consumption of the MURB, but these retrofits ensured that safe indoor conditions were maintained throughout the year. The electrification of space heating and DHW systems was the most effective in reducing operational carbon emissions. The final retrofit package, which included envelope retrofits and mechanical system upgrades, achieved a 57% reduction in EUI and a 90% reduction in operational carbon emissions.

Under future climate conditions, the elevated outdoor air temperatures reduced overall energy use due to significant reductions in heating energy demand, which outweighed the increases in cooling energy demand. Considerations for the thermal stress and thermal resilience of MURBs became more critical under future climate conditions as the hours of safety were reduced by up to 47.4%.

## 5.1 Future Work

This study presents several opportunities for future work. It would be valuable to apply the predictive models to other mid-rise MURBs with known natural gas and electricity consumptions and compare the predicted EUIs with the actual EUI calculated using the consumption data. Furthermore, the surrogate modelling methodology used in this study could be expanded to encompass a wider range of ECMs and building parameters to create surrogate models that are more representative of a larger diversity of MURBs.

The predictive models could also be built upon and used for multi-objective optimization of the KPIs studied. A further contribution would be for the surrogate models to not only predict the EUI of the MURB but also thermal stress or thermal resilience metrics. In this way, the model could be used to minimize EUI while keeping thermal stress and thermal resilience within an acceptable threshold. Cost could also be added as a KPI in this multi-objective optimization.

It would also be valuable to include future grid emissions factors in the operational carbon emission calculations. This will better reflect the impact of electrification on the annual operational carbon emissions of MURBs.

The thermal resilience analysis could be expanded by simulating power outage conditions during periods of extreme hot and cold temperatures and assessing the building's hours of safety. Extended outage events are relatively uncommon in Toronto; however, climate change is expected to increase their frequency and severity. Several methodologies for implementing thermal resilience simulations have been published; however, there is currently no industry-standard approach.

An unexpected finding in this study was that, under a very high-performing envelope, switching from natural gas heating to an ASHP increased heating energy consumption; however, under more typical envelopes, switching to an ASHP reduced heating energy consumption. Further study should be conducted to determine the optimal balance between building envelope upgrades and HVAC upgrades for minimizing energy consumption.

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## Appendix A - Statistical Analysis of Climate File Differences

### A.1 Objective

The objective of this analysis is to quantify the statistical differences between selected weather files using monthly HDD (base 18°C) and CDD (base 18°C), and to assess the implications for weather file substitution in calibrated building models.

### A.2 Method

For each pairing of weather files, the following metrics were computed:

1. MBE which captures systematic warm and cool bias, and
2. MAE/RMSE which capture overall difference magnitude

Both HDD and CDD were computed using a base temperature of 18°C. Monthly data from the weather files were used, with n=12. Note that the baseline model has no cooling system, whereas only the ECM models with HVAC types B and C include cooling. Therefore, while statistical comparisons are presented for both HDD and CDD, the baseline model's energy use does not include any cooling contribution. However, the CDD analysis is presented due to thermal stress and resilience analysis.

### A.3 Interpretation

Table A.1 summarizes the MBE, MAE and RMSE results when comparing (1) the current Toronto TMY data with the current Calgary TMY data, and (2) the current Toronto TMY data to the future Toronto TMY data (GW3.5).

**Table A.1: Statistical Analysis of Climate File Differences**

| Statistical Metrics |      | Current Toronto TMY vs.<br>Current Calgary TMY<br>(degree-days) | Current Toronto TMY vs.<br>Future Toronto TMY<br>(GW3.5)<br>(degree-days) |
|---------------------|------|-----------------------------------------------------------------|---------------------------------------------------------------------------|
| HDD<br>(base 18°C)  | MBE  | 112.3                                                           | -109.5                                                                    |
|                     | MAE  | 112.3                                                           | 109.5                                                                     |
|                     | RMSE | 124.5                                                           | 134.1                                                                     |
| CDD<br>(base 18°C)  | MBE  | -19.2                                                           | -39.3                                                                     |
|                     | MAE  | 19.2                                                            | 39.3                                                                      |
|                     | RMSE | 37.2                                                            | 66.2                                                                      |

The MBE and RMSE for HDD between current Toronto TMY data and current Calgary TMY data (MBE = 112.3 DD and RMSE = 124.5 DD) are comparable in magnitude to the MBE and RMSE between current Toronto TMY data and future Toronto TMY data (MBE = -109.5 and RMSE = 134.1 DD), indicating a similar heating demand deviation.

For CDD, the MBE and RMSE between current Toronto TMY data and current Calgary TMY data (MBE = -19.2 DD and RMSE = 37.2 DD) are notably smaller than those between current Toronto TMY data and future Toronto TMY data (MBE = -39.3 DD and RMSE = 66.2 DD). This indicates that the projected future climate scenario (GW3.5) for Toronto is expected to result in a greater increase in cooling demand deviation relative to current conditions than the difference observed between the current climates of Toronto and Calgary. Figures A.1 and A.2 show the HDD and CDD comparisons for the three different weather files.

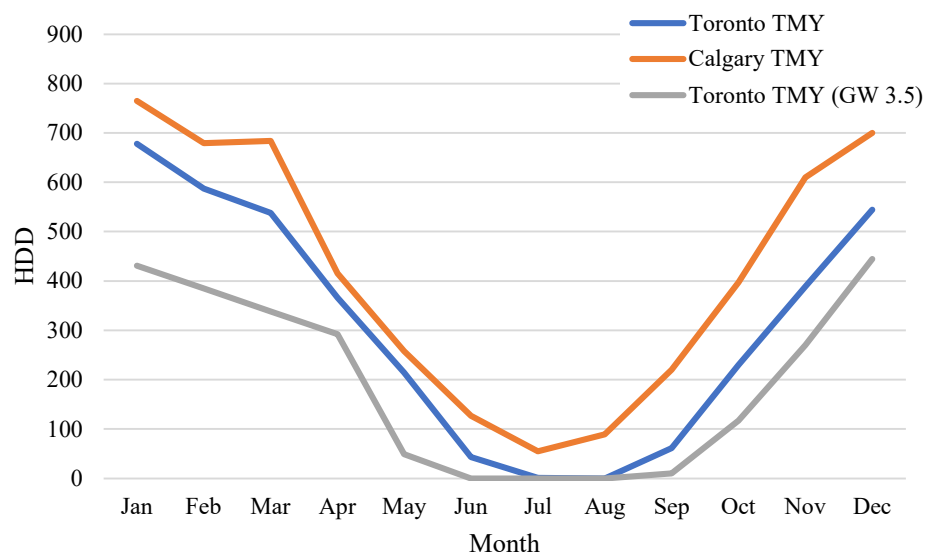


**Figure A.1: HDD Comparison**

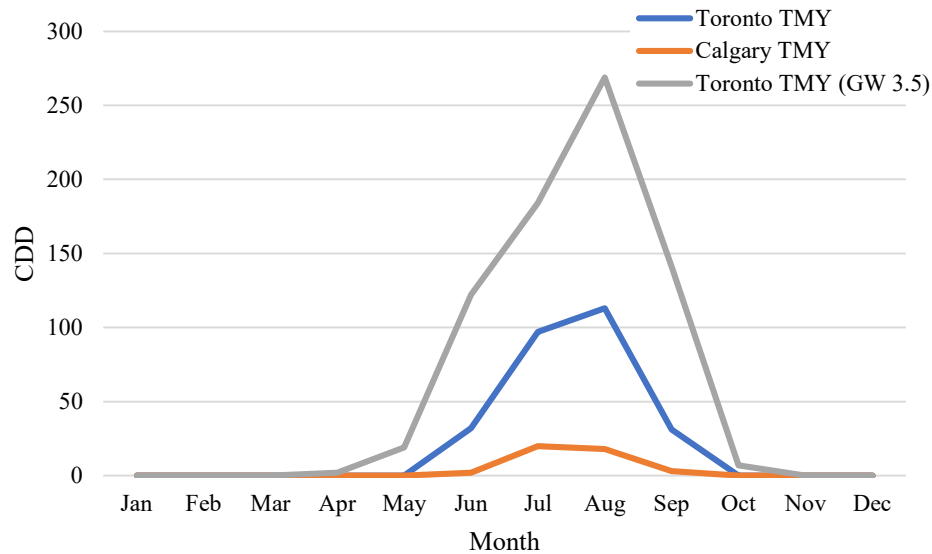


**Figure A.2: CDD Comparison**

From a purely HDD/CDD perspective, Calgary’s current climate is statistically closer to Toronto’s current climate than Toronto’s projected future climate is. This raises the question of whether, given acceptance of future weather files in certain calibrated modelling contexts, similar acceptance could be considered for alternate-location files with smaller degree day differences, when measured performance data is not available for a given location.

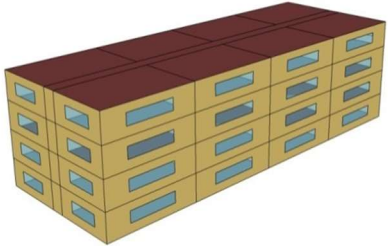
#### **A.4 Limitations**

Note that HDD/CDD capture temperature-driven loads but not the influence of humidity, solar gains, precipitation, or wind. These can significantly alter building performance. So, substituting a different location may still introduce representativeness concerns beyond degree-days. Also, MBE does not distinguish between systematic offset and seasonal mismatch while RMSE penalises extremes but does not explain timing.

It should be noted that while this method can be suitable for generating synthetic datasets for surrogate modeling analysis, it is not appropriate for regulatory or certification purposes (e.g., compliance modeling or incentive programs), where strict geographic and project-specific calibration is required.

## Appendix B - Baseline Model Calibration

**Table B.1: Comparison of the Baseline Model and Reference Building Specifications**

| Case Study Building                                                               |                                                                                                         | Archetype Model<br>DOE Mid-Rise Apartment                                                       |
|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
|  |                                                                                                         |              |
| <b>Form</b>                                                                       |                                                                                                         |                                                                                                 |
| Year Built                                                                        | 1971                                                                                                    | N/A                                                                                             |
| # of Floors                                                                       | 6 + 1 (parking)                                                                                         | 4                                                                                               |
| # of Units                                                                        | 35                                                                                                      | 23                                                                                              |
| # of Units/Floor                                                                  | 3 1-Bedroom Units, 3 2-Bedroom, 1 Mechanical Room on 2nd Floor                                          | 8 1-Bedroom Units, 1 Office on Ground Floor                                                     |
| # of 1-Bedroom Units                                                              | 17                                                                                                      | 23                                                                                              |
| # of 2-Bedroom Units                                                              | 18                                                                                                      | -                                                                                               |
| # of Occupants/Unit                                                               | 1-Bedroom: 2, 2-Bedrooms: 3                                                                             | 2.5                                                                                             |
| WWR                                                                               | 13.46%                                                                                                  | 20.00%                                                                                          |
| Footprint Area                                                                    | 465 m <sup>2</sup> (5000 ft <sup>2</sup> )                                                              | 784 m <sup>2</sup> (8,436 ft <sup>2</sup> )                                                     |
| Total Floor Area                                                                  | 2787 m <sup>2</sup> (30,000 ft <sup>2</sup> )                                                           | 3131 m <sup>2</sup> (33,700 ft <sup>2</sup> )                                                   |
| Total Conditioned Area                                                            | 2369 m <sup>2</sup> (25,500 ft <sup>2</sup> )                                                           | 2824 m <sup>2</sup> (30,400 ft <sup>2</sup> )                                                   |
| Total Unconditioned Area                                                          | 46 m <sup>2</sup> (500 ft <sup>2</sup> )                                                                | 307 m <sup>2</sup> (3,300 ft <sup>2</sup> )                                                     |
| 1-Bedroom Unit Area                                                               | 53 m <sup>2</sup> (575 ft <sup>2</sup> )                                                                | 88 m <sup>2</sup> (950 ft <sup>2</sup> )                                                        |
| 2-Bedroom Unit Area                                                               | 82 m <sup>2</sup> (884 ft <sup>2</sup> )                                                                | -                                                                                               |
| Corridor Area                                                                     | 58 m <sup>2</sup> (623 ft <sup>2</sup> )                                                                | 78 m <sup>2</sup> (836 ft <sup>2</sup> )                                                        |
| Aspect Ratio                                                                      | 1.19                                                                                                    | 2.74                                                                                            |
| <b>Building Envelope</b>                                                          |                                                                                                         |                                                                                                 |
| Exterior Walls                                                                    | Primarily Brick Veneer Masonry, Some Stucco on Main Level                                               | Steel-Frame Walls (2x4 16in oc) 0.4 in. Stucco+5/8 in. Gypsum Board + Wall Insulation+5/8 in.   |
| Roof                                                                              | Concrete Roof Decking, Rigid Insulation, EPDM Membrane (Stairwell/Elevator Penthouse: Modified Bitumen) | Built-Up Roof: Roof Membrane + Roof Insulation + Metal Decking (Insulation Entirely Above Deck) |
| Windows                                                                           | Operable Double Pane SG Units Set Within PVC And Metal Frames Within Punched Openings                   | Follows ASHRAE 90.1 Requirements 100% Operable Area                                             |
| Exterior Shading                                                                  | Balconies                                                                                               | None                                                                                            |

|                            |                                                                                                                                          |                                                                                                                                                                                                                                                                  |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Foundation                 | Cast-in-Place Concrete Slab-on-Grade                                                                                                     | Slab-On-Grade Floors (Unheated)<br>8" Concrete Slab Poured Directly on to The Earth                                                                                                                                                                              |
| Air Tightness              | -                                                                                                                                        | 1.0241 L/s·m <sup>2</sup> (0.2016 cfm/ft <sup>2</sup> ) of Gross Exterior Wall Area (At 10 mph Wind Speed)                                                                                                                                                       |
| Recent Retrofits           | Roof: 2015                                                                                                                               | N/A                                                                                                                                                                                                                                                              |
| <b>HVAC</b>                |                                                                                                                                          |                                                                                                                                                                                                                                                                  |
| Heating                    | Natural Gas-Fired Boiler<br>Supplying Hydronic Baseboards,<br>Natural<br>Gas-Fired Forced Air Furnace<br>Supplying Heat to the Corridors | Gas Furnace                                                                                                                                                                                                                                                      |
| Heating Year Installed     | Boiler: 2015, Furnace: 1971                                                                                                              | -                                                                                                                                                                                                                                                                |
| Heating Capacity           | Boiler: 352 kW (1,200 kBTU/hr)<br>Furnace: 62 kW (211.5 kBTU/hr)                                                                         | Auto Sized                                                                                                                                                                                                                                                       |
| Cooling                    | -                                                                                                                                        | Split System DX (1 Per Apt)                                                                                                                                                                                                                                      |
| Cooling Capacity           | -                                                                                                                                        | Auto Sized                                                                                                                                                                                                                                                       |
| DHW                        | Natural Gas-Fired Boiler                                                                                                                 | Individual Residential Water Heater with Storage Tank<br>Electricity                                                                                                                                                                                             |
| DHW Year Installed         | 2003                                                                                                                                     | -                                                                                                                                                                                                                                                                |
| DHW Input Heating Capacity | 133 kW (454.5 kBTU/hr)                                                                                                                   | Auto Sized                                                                                                                                                                                                                                                       |
| DHW Volume                 | 303 L (80 US Gal.)                                                                                                                       | 189 L (50 US Gal.)                                                                                                                                                                                                                                               |
| <b>Internal Loads</b>      |                                                                                                                                          |                                                                                                                                                                                                                                                                  |
| Equipment                  | Laundry: 2 Electric Washing Machines & 2 Electric Dryers, Units: Electric Stove & Fridge                                                 | 6.6 W/m <sup>2</sup> (2.1 BTU/hr/ft <sup>2</sup> ) Daily Peak Per Apartment, Including All the Home Appliances                                                                                                                                                   |
| Lighting                   | -                                                                                                                                        | Apartment Units: 3.8 W/m <sup>2</sup> (1.2 BTU/hr/ft <sup>2</sup> ) (Daily Peak for Hard-Wired Lighting) and 0.9 W/m <sup>2</sup> (0.3 BTU/hr/ft <sup>2</sup> ) (Daily Peak for Plug-In Lighting), Corridor: 5.4 W/ft <sup>2</sup> (1.7 BTU/hr/ft <sup>2</sup> ) |
| Elevators                  | 1 Elevator                                                                                                                               | 16.1 kW/Elevator (54.8 kBTU/hr/Elevator) Peak Motor Power                                                                                                                                                                                                        |

**Table B.2: High Performance Prescriptive Program Specifications**

| Component     | Thermal Design Guide (CZ 5)                                             | EnerPHit                                                  | PHIUS CORE Prescriptive (New Construction)                   | ASHRAE 90.1 (CZ5)                                                                                                                                                   | ASHRAE Advanced Energy Design Guide for Multifamily Buildings (CZ5a)                                  | NECB (CZ5)                                                    |
|---------------|-------------------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Wall          | RSI- 5.3 (R-30)                                                         | Interior: RSI-2.9 (R-16.2)<br>Exterior: RSI-6.7 (R-37.9)  | RSI-7.7 (R-44)                                               | Mass: RSI- 2.3ci (R-13.3ci)<br>Wood-Framed: RSI-2.3+RSI-1.3 (R-13+R-7.5) or RSI-3.3+RSI-0.9 (R-19+R-5)                                                              | RSI- 8.0 (R-45.5)                                                                                     | RSI-3.8 (R-21.4)                                              |
| Roof          | Vented Roof: RSI-11.4 (R-65)<br>Compact Roof: RSI-8.8 (R-50)            | Exterior Insulation: RSI-6.7 (R-37.9)                     | RSI-13.2 (R-75)                                              | Attic: RSI-8.6 (R-49)<br>Insulation Entirely Above Deck: RSI-5.3ci (R-30ci)                                                                                         | RSI-9.8 (R-55.6)                                                                                      | RSI-6.4 (R-36.4)                                              |
| Windows       | 1.40 W/m <sup>2</sup> ·K (0.25 Btu/h·ft <sup>2</sup> ·°F),<br>0.50 SHGC | 0.85 W/m <sup>2</sup> ·K (0.15 Btu/h·ft <sup>2</sup> ·°F) | 0.90 W/m <sup>2</sup> ·K (0.16 Btu/h·ft <sup>2</sup> ·°F)    | Fixed: 2.04 W/m <sup>2</sup> ·K (0.36 Btu/h·ft <sup>2</sup> ·°F),<br>0.38 SHGC<br>Operable: 2.56 W/m <sup>2</sup> ·K (0.45 Btu/h·ft <sup>2</sup> ·°F),<br>0.33 SHGC | 0.97 W/m <sup>2</sup> ·K (0.17 Btu/h·ft <sup>2</sup> ·°F),<br>Fixed: 0.36 SHGC<br>Operable: 0.31 SHGC | 1.90 W/m <sup>2</sup> ·K (0.33 Btu/h·ft <sup>2</sup> ·°F)     |
| Air Tightness | 2 L/s·m <sup>2</sup> (0.39 cfm/ft <sup>2</sup> )<br>@ 75 Pa             | 1 ACH @ 50 Pa                                             | 0.3 L/s·m <sup>2</sup> (0.06 cfm/ft <sup>2</sup> )<br>@ 50Pa | 1.8 L/s·m <sup>2</sup> (0.35 cfm/ft <sup>2</sup> )<br>@ 75 Pa                                                                                                       | 1.3 L/s·m <sup>2</sup> (0.26 cfm/ft <sup>2</sup> )<br>@ 75 Pa                                         | 1.5 L/s·m <sup>2</sup> (0.30 cfm/ft <sup>2</sup> )<br>@ 75 Pa |

**Table B.3: Comparison of DOE Model and Baseline Model**

| <b>Parameter</b>                         | <b>DOE Model</b> | <b>Baseline Model</b> |
|------------------------------------------|------------------|-----------------------|
| Roof R-Value<br>(m <sup>2</sup> ·K/W)    | 2.60             | 1.92                  |
| Wall R-Value<br>(m <sup>2</sup> ·K/W)    | 1.17             | 0.80                  |
| Window U-Factor<br>(W/m <sup>2</sup> ·K) | 3.38             | 3.38                  |
| Window SHGC                              | 0.39             | 0.10                  |
| LPD<br>(W/m <sup>2</sup> )               | 16.47            | 5.00                  |
| EPD<br>(W/m <sup>2</sup> )               | 6.67             | 7.00                  |
| Infiltration<br>(L/s· m <sup>2</sup> )   | 0.103            | 0.611                 |
| Cooling Schedule                         | Always On        | Always Off            |
| Heating Efficiency                       | 0.80             | 0.60                  |
| DHW Efficiency                           | 1.00             | 0.75                  |
| DHW Peak Flow Rate<br>(L/s)              | 0.00146          | 0.00208               |

## Appendix C - Surrogate Modelling

### C.1 Polynomial Surrogate Model Equations Instructions

The second-, third-, and fourth-degree polynomial surrogate models developed in this study can be used to predict EUI of a mid-rise MURB in Toronto, within the range of design values listed in Table C.1. The first step in using the surrogate models is selecting the equation corresponding to the appropriate HVAC system (A, B, or C). The details of each HVAC system are listed in Table 3.1. With an equation selected, it can be used by simply substituting values for each design value (or ECM) in the polynomial equation. Design values should be selected within the indicated ranges to achieve EUI prediction within the statistical errors presented in Table 4.4, Table 4.5, and Table 4.6. While the author recommends using the fourth-degree polynomial equation for higher prediction accuracy, the second and third-degree equations may also be used, as they can be more practical for implementation in spreadsheets or manual calculations. Although these lower-degree models still provide reasonably accurate predictions, they exhibit greater inherent prediction errors and should be used with this consideration in mind.

Finally, application examples are provided in Table C.2, showing a set of model inputs and the resulting predicted EUI value (rounded to the first decimal point, and including statistical errors) for each of the three polynomial regression models. This example is intended to help users verify the correct implementation of the polynomial models.

**Table C.1: Polynomial Surrogate Model Input Variable Descriptions**

| Variable                                             | ECM                                               | Range             |
|------------------------------------------------------|---------------------------------------------------|-------------------|
| window_u<br>(W/m <sup>2</sup> ·K)                    | Window U-Factor                                   | 0.568 - 3.407     |
| wall_r<br>(m <sup>2</sup> ·K/W)                      | Wall Assembly Effective R-Value                   | 0.704 - 7.045     |
| roof_r<br>(m <sup>2</sup> ·K/W)                      | Roof Assembly Effective R-Value                   | 0.704 - 10.567    |
| infiltration<br>(m <sup>3</sup> /s· m <sup>2</sup> ) | Infiltration Rate Per Exterior Surface Area @4 Pa | 0.00016 - 0.00062 |
| lights<br>(W/m <sup>2</sup> )                        | Lighting Power Density                            | 2 - 12            |
| equipment<br>(W/m <sup>2</sup> )                     | Equipment Power Density                           | 4 - 20            |

**Table C.2: Polynomial Surrogate Model Sample Inputs and Outputs**

| Inputs/Outputs                                                     | Sample 1   | Sample 2   | Sample 3   |
|--------------------------------------------------------------------|------------|------------|------------|
| HVAC System                                                        | A          | B          | C          |
| window_u<br>(W/m <sup>2</sup> ·K)                                  | 2.01       | 3.09       | 0.75       |
| wall_r<br>(m <sup>2</sup> ·K/W)                                    | 2.54       | 3.75       | 4.85       |
| roof_r<br>(m <sup>2</sup> ·K/W)                                    | 8.53       | 7.60       | 9.20       |
| infiltration<br>(m <sup>3</sup> /s· m <sup>2</sup> )               | 0.000541   | 0.000257   | 0.000179   |
| lights<br>(W/m <sup>2</sup> )                                      | 7.45       | 10.68      | 8.50       |
| equipment<br>(W/m <sup>2</sup> )                                   | 11.57      | 17.58      | 6.33       |
| dhw<br>(m <sup>3</sup> /s)                                         | 0.00000501 | 0.00000463 | 0.00000482 |
| EUI from Second-Degree Polynomial Equation<br>(MJ/m <sup>2</sup> ) | 780.19     | 794.63     | 493.31     |
| EUI from Third-Degree Polynomial Equation<br>(MJ/m <sup>2</sup> )  | 785.88     | 800.64     | 494.75     |
| EUI from Fourth-Degree Polynomial Equation<br>(MJ/m <sup>2</sup> ) | 780.70     | 801.47     | 493.02     |

**C.1.1 Second-Degree Polynomial Equation for HVAC A**

$$\begin{aligned}
\text{EUI} = & 294.155 + (28.2147) \cdot \text{window\_u} + (-32.6464) \cdot \text{wall\_r} + (-23.9348) \cdot \text{roof\_r} + \\
& (425132) \cdot \text{infiltration} + (1.40426) \cdot \text{lights} + (8.74566) \cdot \text{equipment} + (3.83686\text{e}+07) \cdot \text{dhw} + \\
& (1.66062) \cdot \text{window\_u}^2 + (-1.62577) \cdot \text{window\_u} \cdot \text{wall\_r} + (-0.125285) \cdot \text{window\_u} \cdot \text{roof\_r} + \\
& (45967.6) \cdot \text{window\_u} \cdot \text{infiltration} + (-0.329936) \cdot \text{window\_u} \cdot \text{lights} + (- \\
& 1.58994) \cdot \text{window\_u} \cdot \text{equipment} + (275419) \cdot \text{window\_u} \cdot \text{dhw} + (3.04196) \cdot \text{wall\_r}^2 + \\
& (0.103806) \cdot \text{wall\_r} \cdot \text{roof\_r} + (-12047) \cdot \text{wall\_r} \cdot \text{infiltration} + (0.0731069) \cdot \text{wall\_r} \cdot \text{lights} + \\
& (0.585409) \cdot \text{wall\_r} \cdot \text{equipment} + (-382678) \cdot \text{wall\_r} \cdot \text{dhw} + (1.56303) \cdot \text{roof\_r}^2 + (- \\
& 6167.06) \cdot \text{roof\_r} \cdot \text{infiltration} + (0.102486) \cdot \text{roof\_r} \cdot \text{lights} + (0.196456) \cdot \text{roof\_r} \cdot \text{equipment} + \\
& (-115239) \cdot \text{roof\_r} \cdot \text{dhw} + (3.31462\text{e}+08) \cdot \text{infiltration}^2 + (- \\
& 5193.11) \cdot \text{infiltration} \cdot \text{lights} + (-20725.3) \cdot \text{infiltration} \cdot \text{equipment} + (- \\
& 3.30586\text{e}+09) \cdot \text{infiltration} \cdot \text{dhw} + (0.0125019) \cdot \text{lights}^2 + (0.154642) \cdot \text{lights} \cdot \text{equipment} + \\
& (111439) \cdot \text{lights} \cdot \text{dhw} + (0.402636) \cdot \text{equipment}^2 + (65724.4) \cdot \text{equipment} \cdot \text{dhw} + \\
& (1.47214\text{e}+12) \cdot \text{dhw}^2
\end{aligned}$$

**C.1.2 Third-Degree Polynomial Equation for HVAC A**

$$\begin{aligned}
\text{EUI} = & 369.731 + (30.758) \cdot \text{window\_u} + (-68.599) \cdot \text{wall\_r} + (-50.8743) \cdot \text{roof\_r} + \\
& (423987) \cdot \text{infiltration} + (-4.10968) \cdot \text{lights} + (4.15524) \cdot \text{equipment} + (5.36993\text{e}+07) \cdot \text{dhw} + \\
& (6.66533) \cdot \text{window\_u}^2 + (-2.99154) \cdot \text{window\_u} \cdot \text{wall\_r} + (-2.26307) \cdot \text{window\_u} \cdot \text{roof\_r} +
\end{aligned}$$

$$\begin{aligned}
& (49877.2)*window\_u*infiltration + (0.0854983)*window\_u*lights + (- \\
& 2.32079)*window\_u*equipment + (417231)*window\_u*dhw + (12.8751)*wall\_r**2 + \\
& (0.70544)*wall\_r*roof\_r + (-31689.8)*wall\_r*infiltration + (-1.00078)*wall\_r*lights + \\
& (2.25438)*wall\_r*equipment + (-715157)*wall\_r*dhw + (6.66292)*roof\_r**2 + (- \\
& 20935.3)*roof\_r*infiltration + (1.35975)*roof\_r*lights + (0.663161)*roof\_r*equipment \\
& + (100898)*roof\_r*dhw + (3.24782e+08)*infiltration**2 + (6016.87)*infiltration*lights \\
& + (-28792.5)*infiltration*equipment + (3.38795e+10)*infiltration*dhw + \\
& (0.0744377)*lights**2 + (0.108721)*lights*equipment + (1.16024e+06)*lights*dhw + \\
& (0.575469)*equipment**2 + (489502)*equipment*dhw + (-6.04368e+12)*dhw**2 + (- \\
& 0.651347)*window\_u**3 + (-0.0710362)*window\_u**2*wall\_r + \\
& (0.0802963)*window\_u**2*roof\_r + (-5911.91)*window\_u**2*infiltration + (- \\
& 0.0471705)*window\_u**2*lights + (0.00286307)*window\_u**2*equipment + \\
& (678.279)*window\_u**2*dhw + (0.344088)*window\_u*wall\_r**2 + (- \\
& 0.0579539)*window\_u*wall\_r*roof\_r + (627.019)*window\_u*wall\_r*infiltration + \\
& (0.128277)*window\_u*wall\_r*lights + (-0.0465945)*window\_u*wall\_r*equipment + (- \\
& 152661)*window\_u*wall\_r*dhw + (0.0293233)*window\_u*roof\_r**2 + \\
& (2014.1)*window\_u*roof\_r*infiltration + (-0.0584051)*window\_u*roof\_r*lights + (- \\
& 0.0441873)*window\_u*roof\_r*equipment + (405656)*window\_u*roof\_r*dhw + (- \\
& 3.38559e+07)*window\_u*infiltration**2 + (-1199.91)*window\_u*infiltration*lights + \\
& (1776.83)*window\_u*infiltration*equipment + (5.14921e+09)*window\_u*infiltration*dhw + \\
& (0.0148706)*window\_u*lights**2 + (0.0141059)*window\_u*lights*equipment + (- \\
& 107942)*window\_u*lights*dhw + (0.00731591)*window\_u*equipment**2 + \\
& (33799.9)*window\_u*equipment*dhw + (-4.07983e+11)*window\_u*dhw**2 + (- \\
& 0.838271)*wall\_r**3 + (0.0215206)*wall\_r**2*roof\_r + (3428.9)*wall\_r**2*infiltration \\
& + (-0.0305733)*wall\_r**2*lights + (-0.125999)*wall\_r**2*equipment + (- \\
& 109083)*wall\_r**2*dhw + (-0.02358)*wall\_r*roof\_r**2 + (- \\
& 535.767)*wall\_r*roof\_r*infiltration + (0.0376656)*wall\_r*roof\_r*lights + (- \\
& 0.00543179)*wall\_r*roof\_r*equipment + (-91532.7)*wall\_r*roof\_r*dhw + \\
& (9.86808e+06)*wall\_r*infiltration**2 + (109.958)*wall\_r*infiltration*lights + (- \\
& 925.319)*wall\_r*infiltration*equipment + (-1.35446e+09)*wall\_r*infiltration*dhw + \\
& (0.0609565)*wall\_r*lights**2 + (-0.00517627)*wall\_r*lights*equipment + \\
& (678.83)*wall\_r*lights*dhw + (-0.00241077)*wall\_r*equipment**2 + (- \\
& 31862.4)*wall\_r*equipment*dhw + (3.7052e+11)*wall\_r*dhw**2 + (-0.336171)*roof\_r**3 + \\
& (976.65)*roof\_r**2*infiltration + (-0.0535396)*roof\_r**2*lights + (- \\
& 0.0238023)*roof\_r**2*equipment + (177989)*roof\_r**2*dhw + \\
& (4.26473e+06)*roof\_r*infiltration**2 + (-606.409)*roof\_r*infiltration*lights + (- \\
& 390.817)*roof\_r*infiltration*equipment + (2.28169e+09)*roof\_r*infiltration*dhw + (- \\
& 0.00660716)*roof\_r*lights**2 + (0.000346645)*roof\_r*lights*equipment + (- \\
& 88434.8)*roof\_r*lights*dhw + (0.00745023)*roof\_r*equipment**2 + (- \\
& 26664.4)*roof\_r*equipment*dhw + (-3.2385e+11)*roof\_r*dhw**2 + (- \\
& 3.12952e+11)*infiltration**3 + (4.10112e+06)*infiltration**2*lights + \\
& (2.68474e+07)*infiltration**2*equipment + (2.36121e+12)*infiltration**2*dhw + \\
& (96.3378)*infiltration*lights**2 + (71.4001)*infiltration*lights*equipment + (- \\
& 2.43425e+09)*infiltration*lights*dhw + (-386.246)*infiltration*equipment**2 + (- \\
& 5.00316e+08)*infiltration*equipment*dhw + (-3.08455e+15)*infiltration*dhw**2 + (- \\
& 0.00852288)*lights**3 + (-0.00291334)*lights**2*equipment + (-26576.4)*lights**2*dhw \\
& + (-0.000404137)*lights*equipment**2 + (16707.4)*lights*equipment*dhw + \\
& (8.52014e+10)*lights*dhw**2 + (-0.00364937)*equipment**3 + (19506)*equipment**2*dhw + \\
& (-8.23758e+10)*equipment*dhw**2 + (8.03015e+17)*dhw**3
\end{aligned}$$

### C.1.3 Fourth-Degree Polynomial Equation for HVAC A

$$\begin{aligned}
EUI = & 353.861 + (33.0374)*window\_u + (-82.1426)*wall\_r + (-62.9945)*roof\_r + \\
& (138863)*infiltration + (-4.38188)*lights + (7.51771)*equipment + (8.61515e+07)*dhw + \\
& (4.16757)*window\_u**2 + (-10.4716)*window\_u*wall\_r + (-0.0247106)*window\_u*roof\_r + \\
& (54972)*window\_u*infiltration + (-2.16532)*window\_u*lights + (-
\end{aligned}$$

3.22447)\*window\_u\*equipment + (1.17467e+07)\*window\_u\*dhw + (21.6349)\*wall\_r\*\*2 +  
 (0.0747411)\*wall\_r\*roof\_r + (493.797)\*wall\_r\*infiltration + (-1.42481)\*wall\_r\*lights  
 + (3.6849)\*wall\_r\*equipment + (-6.79367e+06)\*wall\_r\*dhw + (13.1589)\*roof\_r\*\*2 +  
 (10823.1)\*roof\_r\*infiltration + (2.11237)\*roof\_r\*lights + (-  
 0.854382)\*roof\_r\*equipment + (-4.84789e+06)\*roof\_r\*dhw +  
 (3.83521e+08)\*infiltration\*\*2 + (32681.1)\*infiltration\*lights + (-  
 8079.25)\*infiltration\*equipment + (2.75098e+10)\*infiltration\*dhw +  
 (0.476651)\*lights\*\*2 + (-0.208013)\*lights\*equipment + (-981417)\*lights\*dhw +  
 (0.272758)\*equipment\*\*2 + (-12705.6)\*equipment\*dhw + (-6.25547e+12)\*dhw\*\*2 +  
 (2.00768)\*window\_u\*\*3 + (0.126939)\*window\_u\*\*2\*wall\_r + (0.554451)\*window\_u\*\*2\*roof\_r  
 + (-11222.9)\*window\_u\*\*2\*infiltration + (-0.00749376)\*window\_u\*\*2\*lights + (-  
 0.315047)\*window\_u\*\*2\*equipment + (-3.12224e+06)\*window\_u\*\*2\*dhw +  
 (0.828478)\*window\_u\*wall\_r\*\*2 + (0.36181)\*window\_u\*wall\_r\*roof\_r +  
 (12089.9)\*window\_u\*wall\_r\*infiltration + (0.000315263)\*window\_u\*wall\_r\*lights + (-  
 0.0435637)\*window\_u\*wall\_r\*equipment + (892782)\*window\_u\*wall\_r\*dhw + (-  
 0.247914)\*window\_u\*roof\_r\*\*2 + (3864.21)\*window\_u\*roof\_r\*infiltration + (-  
 0.0660743)\*window\_u\*roof\_r\*lights + (-0.157693)\*window\_u\*roof\_r\*equipment + (-  
 353235)\*window\_u\*roof\_r\*dhw + (-4.30464e+07)\*window\_u\*infiltration\*\*2 + (-  
 1447.43)\*window\_u\*infiltration\*lights + (2858.07)\*window\_u\*infiltration\*equipment +  
 (-4.48136e+09)\*window\_u\*infiltration\*dhw + (0.257236)\*window\_u\*lights\*\*2 +  
 (0.327229)\*window\_u\*lights\*equipment + (-814152)\*window\_u\*lights\*dhw +  
 (0.0725605)\*window\_u\*equipment\*\*2 + (-274486)\*window\_u\*equipment\*dhw +  
 (9.58897e+10)\*window\_u\*dhw\*\*2 + (-3.60316)\*wall\_r\*\*3 + (0.164092)\*wall\_r\*\*2\*roof\_r +  
 (14655.7)\*wall\_r\*\*2\*infiltration + (0.235947)\*wall\_r\*\*2\*lights + (-  
 0.538061)\*wall\_r\*\*2\*equipment + (2.00208e+06)\*wall\_r\*\*2\*dhw + (-  
 0.0523532)\*wall\_r\*roof\_r\*\*2 + (-3277.1)\*wall\_r\*roof\_r\*infiltration + (-  
 0.163339)\*wall\_r\*roof\_r\*lights + (0.00621161)\*wall\_r\*roof\_r\*equipment +  
 (290856)\*wall\_r\*roof\_r\*dhw + (7.77685e+06)\*wall\_r\*infiltration\*\*2 +  
 (1830.64)\*wall\_r\*infiltration\*lights + (-6177.06)\*wall\_r\*infiltration\*equipment + (-  
 2.51109e+10)\*wall\_r\*infiltration\*dhw + (0.152324)\*wall\_r\*lights\*\*2 +  
 (0.0166978)\*wall\_r\*lights\*equipment + (-106498)\*wall\_r\*lights\*dhw + (-  
 0.0432375)\*wall\_r\*equipment\*\*2 + (581579)\*wall\_r\*equipment\*dhw +  
 (1.02788e+11)\*wall\_r\*dhw\*\*2 + (-1.53148)\*roof\_r\*\*3 + (4641.73)\*roof\_r\*\*2\*infiltration  
 + (-0.143501)\*roof\_r\*\*2\*lights + (0.0626225)\*roof\_r\*\*2\*equipment +  
 (968784)\*roof\_r\*\*2\*dhw + (-7.40659e+07)\*roof\_r\*infiltration\*\*2 + (-  
 3111.99)\*roof\_r\*infiltration\*lights + (-1438.39)\*roof\_r\*infiltration\*equipment +  
 (5.38733e+09)\*roof\_r\*infiltration\*dhw + (0.0429023)\*roof\_r\*lights\*\*2 +  
 (0.0516186)\*roof\_r\*lights\*equipment + (-303557)\*roof\_r\*lights\*dhw +  
 (0.0755841)\*roof\_r\*equipment\*\*2 + (79431.1)\*roof\_r\*equipment\*dhw +  
 (1.78005e+11)\*roof\_r\*dhw\*\*2 + (3.51887e+11)\*infiltration\*\*3 + (-  
 2.63844e+07)\*infiltration\*\*2\*lights + (-8.11295e+06)\*infiltration\*\*2\*equipment +  
 (7.14168e+13)\*infiltration\*\*2\*dhw + (144.537)\*infiltration\*lights\*\*2 + (-  
 2704.58)\*infiltration\*lights\*equipment + (-2.05958e+09)\*infiltration\*lights\*dhw +  
 (691.716)\*infiltration\*equipment\*\*2 + (-1.45902e+09)\*infiltration\*equipment\*dhw +  
 (4.37415e+15)\*infiltration\*dhw\*\*2 + (-0.227277)\*lights\*\*3 +  
 (0.108972)\*lights\*\*2\*equipment + (333668)\*lights\*\*2\*dhw + (-  
 0.0158151)\*lights\*equipment\*\*2 + (-57359.4)\*lights\*equipment\*dhw +  
 (4.53369e+11)\*lights\*dhw\*\*2 + (-0.00645548)\*equipment\*\*3 + (73242.2)\*equipment\*\*2\*dhw  
 + (-3.0482e+11)\*equipment\*dhw\*\*2 + (-8.04805e+17)\*dhw\*\*3 + (-0.150007)\*window\_u\*\*4 +  
 (0.047114)\*window\_u\*\*3\*wall\_r + (-0.11219)\*window\_u\*\*3\*roof\_r +  
 (2224.95)\*window\_u\*\*3\*infiltration + (-0.0739158)\*window\_u\*\*3\*lights + (-  
 0.0147727)\*window\_u\*\*3\*equipment + (-134415)\*window\_u\*\*3\*dhw + (-  
 0.0125304)\*window\_u\*\*2\*wall\_r\*\*2 + (0.00247577)\*window\_u\*\*2\*wall\_r\*roof\_r +  
 (332.966)\*window\_u\*\*2\*wall\_r\*infiltration + (0.0103764)\*window\_u\*\*2\*wall\_r\*lights +  
 (-0.00596051)\*window\_u\*\*2\*wall\_r\*equipment + (-35013.6)\*window\_u\*\*2\*wall\_r\*dhw +

(0.00286027)\*window\_u\*\*2\*roof\_r\*\*2 + (-2009.41)\*window\_u\*\*2\*roof\_r\*infiltration +  
 (0.00530657)\*window\_u\*\*2\*roof\_r\*lights + (0.0167383)\*window\_u\*\*2\*roof\_r\*equipment +  
 (138789)\*window\_u\*\*2\*roof\_r\*dhw + (-9.81162e+06)\*window\_u\*\*2\*infiltration\*\*2 +  
 (1539.54)\*window\_u\*\*2\*infiltration\*lights +  
 (249.53)\*window\_u\*\*2\*infiltration\*equipment + (-  
 6.57285e+08)\*window\_u\*\*2\*infiltration\*dhw + (0.000221635)\*window\_u\*\*2\*lights\*\*2 + (-  
 0.0278303)\*window\_u\*\*2\*lights\*equipment + (39331.9)\*window\_u\*\*2\*lights\*dhw +  
 (0.013494)\*window\_u\*\*2\*equipment\*\*2 + (54318.7)\*window\_u\*\*2\*equipment\*dhw +  
 (2.57336e+11)\*window\_u\*\*2\*dhw\*\*2 + (-0.104583)\*window\_u\*wall\_r\*\*3 +  
 (0.00246423)\*window\_u\*wall\_r\*\*2\*roof\_r + (-841.673)\*window\_u\*wall\_r\*\*2\*infiltration +  
 (0.0110842)\*window\_u\*wall\_r\*\*2\*lights + (0.00731432)\*window\_u\*wall\_r\*\*2\*equipment +  
 (182151)\*window\_u\*wall\_r\*\*2\*dhw + (-0.00390113)\*window\_u\*wall\_r\*roof\_r\*\*2 +  
 (81.6297)\*window\_u\*wall\_r\*roof\_r\*infiltration + (-  
 0.0220116)\*window\_u\*wall\_r\*roof\_r\*lights + (-  
 0.00611399)\*window\_u\*wall\_r\*roof\_r\*equipment + (-35248.3)\*window\_u\*wall\_r\*roof\_r\*dhw  
 + (2.97412e+06)\*window\_u\*wall\_r\*infiltration\*\*2 + (-  
 599.301)\*window\_u\*wall\_r\*infiltration\*lights +  
 (249.493)\*window\_u\*wall\_r\*infiltration\*equipment + (-  
 1.3067e+09)\*window\_u\*wall\_r\*infiltration\*dhw + (-0.0152658)\*window\_u\*wall\_r\*lights\*\*2  
 + (0.00398207)\*window\_u\*wall\_r\*lights\*equipment + (106315)\*window\_u\*wall\_r\*lights\*dhw  
 + (0.00193538)\*window\_u\*wall\_r\*equipment\*\*2 + (-49579)\*window\_u\*wall\_r\*equipment\*dhw  
 + (-1.90459e+11)\*window\_u\*wall\_r\*dhw\*\*2 + (0.0160564)\*window\_u\*roof\_r\*\*3 + (-  
 99.7628)\*window\_u\*roof\_r\*\*2\*infiltration + (0.00632527)\*window\_u\*roof\_r\*\*2\*lights +  
 (0.00135469)\*window\_u\*roof\_r\*\*2\*equipment + (-4613.61)\*window\_u\*roof\_r\*\*2\*dhw + (-  
 1.78411e+06)\*window\_u\*roof\_r\*infiltration\*\*2 +  
 (541.148)\*window\_u\*roof\_r\*infiltration\*lights +  
 (278.246)\*window\_u\*roof\_r\*infiltration\*equipment +  
 (2.43162e+06)\*window\_u\*roof\_r\*infiltration\*dhw +  
 (0.000915193)\*window\_u\*roof\_r\*lights\*\*2 +  
 (0.00280608)\*window\_u\*roof\_r\*lights\*equipment + (-41759.4)\*window\_u\*roof\_r\*lights\*dhw  
 + (0.00058419)\*window\_u\*roof\_r\*equipment\*\*2 + (-  
 18614.5)\*window\_u\*roof\_r\*equipment\*dhw + (7.62221e+10)\*window\_u\*roof\_r\*dhw\*\*2 +  
 (7.98353e+10)\*window\_u\*infiltration\*\*3 + (-  
 9.31905e+06)\*window\_u\*infiltration\*\*2\*lights + (-  
 330962)\*window\_u\*infiltration\*\*2\*equipment +  
 (5.59307e+11)\*window\_u\*infiltration\*\*2\*dhw + (-  
 32.5913)\*window\_u\*infiltration\*lights\*\*2 + (-  
 124.825)\*window\_u\*infiltration\*lights\*equipment +  
 (1.06755e+09)\*window\_u\*infiltration\*lights\*dhw + (-  
 114.678)\*window\_u\*infiltration\*equipment\*\*2 + (-  
 5.68607e+07)\*window\_u\*infiltration\*equipment\*dhw +  
 (6.03549e+14)\*window\_u\*infiltration\*dhw\*\*2 + (0.00217307)\*window\_u\*lights\*\*3 + (-  
 0.00579347)\*window\_u\*lights\*\*2\*equipment + (-28904)\*window\_u\*lights\*\*2\*dhw + (-  
 0.00272418)\*window\_u\*lights\*equipment\*\*2 + (-14615.2)\*window\_u\*lights\*equipment\*dhw +  
 (6.23284e+10)\*window\_u\*lights\*dhw\*\*2 + (-0.00134959)\*window\_u\*equipment\*\*3 + (-  
 3949.33)\*window\_u\*equipment\*\*2\*dhw + (8.41882e+10)\*window\_u\*equipment\*dhw\*\*2 + (-  
 2.16988e+17)\*window\_u\*dhw\*\*3 + (0.228734)\*wall\_r\*\*4 + (-0.0202221)\*wall\_r\*\*3\*roof\_r +  
 (-937.635)\*wall\_r\*\*3\*infiltration + (-0.010417)\*wall\_r\*\*3\*lights +  
 (0.0391342)\*wall\_r\*\*3\*equipment + (-116759)\*wall\_r\*\*3\*dhw + (-  
 0.00399508)\*wall\_r\*\*2\*roof\_r\*\*2 + (117.859)\*wall\_r\*\*2\*roof\_r\*infiltration +  
 (0.00377781)\*wall\_r\*\*2\*roof\_r\*lights + (0.000369224)\*wall\_r\*\*2\*roof\_r\*equipment +  
 (2800.53)\*wall\_r\*\*2\*roof\_r\*dhw + (-5.86693e+06)\*wall\_r\*\*2\*infiltration\*\*2 + (-  
 55.6941)\*wall\_r\*\*2\*infiltration\*lights + (289.179)\*wall\_r\*\*2\*infiltration\*equipment +  
 (5.06662e+08)\*wall\_r\*\*2\*infiltration\*dhw + (-0.0170558)\*wall\_r\*\*2\*lights\*\*2 +  
 (0.00302271)\*wall\_r\*\*2\*lights\*equipment + (14407.8)\*wall\_r\*\*2\*lights\*dhw + (-

0.000380641)\*wall\_r\*\*2\*equipment\*\*2 + (-45309.3)\*wall\_r\*\*2\*equipment\*dhw + (-  
 1.10669e+11)\*wall\_r\*\*2\*dhw\*\*2 + (0.00431068)\*wall\_r\*roof\_r\*\*3 + (-  
 63.8332)\*wall\_r\*roof\_r\*\*2\*infiltration + (-0.00736495)\*wall\_r\*roof\_r\*\*2\*lights +  
 (0.0067097)\*wall\_r\*roof\_r\*\*2\*equipment + (1518.07)\*wall\_r\*roof\_r\*\*2\*dhw +  
 (3.1432e+06)\*wall\_r\*roof\_r\*infiltration\*\*2 +  
 (74.6054)\*wall\_r\*roof\_r\*infiltration\*lights + (-  
 45.2683)\*wall\_r\*roof\_r\*infiltration\*equipment +  
 (4.17729e+07)\*wall\_r\*roof\_r\*infiltration\*dhw + (0.00888236)\*wall\_r\*roof\_r\*lights\*\*2 +  
 (0.00248502)\*wall\_r\*roof\_r\*lights\*equipment + (17957.9)\*wall\_r\*roof\_r\*lights\*dhw + (-  
 0.002297)\*wall\_r\*roof\_r\*equipment\*\*2 + (-2475.56)\*wall\_r\*roof\_r\*equipment\*dhw + (-  
 4.1669e+10)\*wall\_r\*roof\_r\*dhw\*\*2 + (3.90481e+10)\*wall\_r\*infiltration\*\*3 + (-  
 3.46007e+06)\*wall\_r\*infiltration\*\*2\*lights + (-  
 461537)\*wall\_r\*infiltration\*\*2\*equipment + (2.91439e+12)\*wall\_r\*infiltration\*\*2\*dhw +  
 (-182.482)\*wall\_r\*infiltration\*lights\*\*2 +  
 (57.5927)\*wall\_r\*infiltration\*lights\*equipment +  
 (8.11267e+08)\*wall\_r\*infiltration\*lights\*dhw +  
 (99.0489)\*wall\_r\*infiltration\*equipment\*\*2 +  
 (6.71836e+07)\*wall\_r\*infiltration\*equipment\*dhw +  
 (1.5195e+15)\*wall\_r\*infiltration\*dhw\*\*2 + (0.00171157)\*wall\_r\*lights\*\*3 +  
 (0.000498309)\*wall\_r\*lights\*\*2\*equipment + (763.26)\*wall\_r\*lights\*\*2\*dhw + (-  
 0.00136573)\*wall\_r\*lights\*equipment\*\*2 + (-14874.2)\*wall\_r\*lights\*equipment\*dhw + (-  
 6.11062e+10)\*wall\_r\*lights\*dhw\*\*2 + (0.000118735)\*wall\_r\*equipment\*\*3 +  
 (4537.62)\*wall\_r\*equipment\*\*2\*dhw + (-1.88046e+10)\*wall\_r\*equipment\*dhw\*\*2 +  
 (1.22288e+17)\*wall\_r\*dhw\*\*3 + (0.0670689)\*roof\_r\*\*4 + (-  
 161.377)\*roof\_r\*\*3\*infiltration + (0.00324875)\*roof\_r\*\*3\*lights + (-  
 0.000349845)\*roof\_r\*\*3\*equipment + (-71905.7)\*roof\_r\*\*3\*dhw +  
 (780359)\*roof\_r\*\*2\*infiltration\*\*2 + (19.3497)\*roof\_r\*\*2\*infiltration\*lights +  
 (5.96338)\*roof\_r\*\*2\*infiltration\*equipment + (-  
 3.59324e+08)\*roof\_r\*\*2\*infiltration\*dhw + (-0.0023396)\*roof\_r\*\*2\*lights\*\*2 +  
 (0.00206796)\*roof\_r\*\*2\*lights\*equipment + (18905.9)\*roof\_r\*\*2\*lights\*dhw + (-  
 0.00135907)\*roof\_r\*\*2\*equipment\*\*2 + (-23161)\*roof\_r\*\*2\*equipment\*dhw +  
 (7.07052e+10)\*roof\_r\*\*2\*dhw\*\*2 + (1.66157e+10)\*roof\_r\*infiltration\*\*3 +  
 (1.26675e+06)\*roof\_r\*infiltration\*\*2\*lights +  
 (2.87217e+06)\*roof\_r\*infiltration\*\*2\*equipment + (-  
 4.92972e+11)\*roof\_r\*infiltration\*\*2\*dhw + (-34.4714)\*roof\_r\*infiltration\*lights\*\*2 +  
 (-35.7749)\*roof\_r\*infiltration\*lights\*equipment +  
 (3.47031e+08)\*roof\_r\*infiltration\*lights\*dhw + (-  
 88.7769)\*roof\_r\*infiltration\*equipment\*\*2 +  
 (1.37886e+08)\*roof\_r\*infiltration\*equipment\*dhw + (-  
 6.01346e+14)\*roof\_r\*infiltration\*dhw\*\*2 + (0.000304031)\*roof\_r\*lights\*\*3 + (-  
 0.00237106)\*roof\_r\*lights\*\*2\*equipment + (-6313.47)\*roof\_r\*lights\*\*2\*dhw + (-  
 0.00182353)\*roof\_r\*lights\*equipment\*\*2 + (947.862)\*roof\_r\*lights\*equipment\*dhw +  
 (1.58808e+09)\*roof\_r\*lights\*dhw\*\*2 + (0.000548451)\*roof\_r\*equipment\*\*3 + (-  
 4971.61)\*roof\_r\*equipment\*\*2\*dhw + (3.45306e+10)\*roof\_r\*equipment\*dhw\*\*2 + (-  
 1.20486e+17)\*roof\_r\*dhw\*\*3 + (-7.27599e+14)\*infiltration\*\*4 +  
 (4.56202e+09)\*infiltration\*\*3\*lights + (4.68224e+10)\*infiltration\*\*3\*equipment + (-  
 1.0133e+17)\*infiltration\*\*3\*dhw + (-5612.14)\*infiltration\*\*2\*lights\*\*2 +  
 (1.77078e+06)\*infiltration\*\*2\*lights\*equipment +  
 (6.25932e+12)\*infiltration\*\*2\*lights\*dhw + (-  
 1.77867e+06)\*infiltration\*\*2\*equipment\*\*2 + (-  
 6.503e+11)\*infiltration\*\*2\*equipment\*dhw + (3.71497e+17)\*infiltration\*\*2\*dhw\*\*2 + (-  
 17.9661)\*infiltration\*lights\*\*3 + (32.3867)\*infiltration\*lights\*\*2\*equipment +  
 (1.65621e+08)\*infiltration\*lights\*\*2\*dhw + (50.4262)\*infiltration\*lights\*equipment\*\*2  
 + (-3.96087e+07)\*infiltration\*lights\*equipment\*dhw + (-  
 1.46695e+15)\*infiltration\*lights\*dhw\*\*2 + (9.60219)\*infiltration\*equipment\*\*3 +

$$\begin{aligned}
& (6.1435e+06)*infiltration*equipment**2*dhw + \\
& (7.95232e+13)*infiltration*equipment*dhw**2 + (-8.93675e+19)*infiltration*dhw**3 + \\
& (0.00561174)*lights**4 + (-0.00266397)*lights**3*equipment + (22392.8)*lights**3*dhw \\
& + (-0.0017113)*lights**2*equipment**2 + (-1696.46)*lights**2*equipment*dhw + (- \\
& 9.45862e+10)*lights**2*dhw**2 + (0.000930313)*lights*equipment**3 + \\
& (1339.74)*lights*equipment**2*dhw + (1.77753e+10)*lights*equipment*dhw**2 + \\
& (9.64144e+16)*lights*dhw**3 + (-0.000199232)*equipment**4 + (- \\
& 117.74)*equipment**3*dhw + (-5.38259e+09)*equipment**2*dhw**2 + (- \\
& 4.04341e+15)*equipment*dhw**3 + (1.67819e+23)*dhw**4
\end{aligned}$$

#### C.1.4 Second-Degree Polynomial Equation for HVAC B

$$\begin{aligned}
EUI = & 149.545 + (6.70184)*window\_u + (-8.95522)*wall\_r + (-6.68548)*roof\_r + \\
& (157681)*infiltration + (2.30782)*lights + (19.5912)*equipment + (4.83123e+07)*dhw + \\
& (1.41584)*window\_u**2 + (-0.895429)*window\_u*wall\_r + (-0.363054)*window\_u*roof\_r + \\
& (31143.1)*window\_u*infiltration + (-0.401427)*window\_u*lights + (- \\
& 1.04197)*window\_u*equipment + (323232)*window\_u*dhw + (0.994173)*wall\_r**2 + \\
& (0.0167447)*wall\_r*roof\_r + (-11639.4)*wall\_r*infiltration + (0.144861)*wall\_r*lights \\
& + (0.380325)*wall\_r*equipment + (-238173)*wall\_r*dhw + (0.533917)*roof\_r**2 + (- \\
& 4427.09)*roof\_r*infiltration + (0.0135307)*roof\_r*lights + \\
& (0.140137)*roof\_r*equipment + (-206990)*roof\_r*dhw + (2.03903e+08)*infiltration**2 + \\
& (-3068.28)*infiltration*lights + (-13947)*infiltration*equipment + \\
& (3.29917e+08)*infiltration*dhw + (0.0267184)*lights**2 + (0.125071)*lights*equipment \\
& + (-34643.7)*lights*dhw + (0.275072)*equipment**2 + (-36532.6)*equipment*dhw + \\
& (3.4224e+11)*dhw**2
\end{aligned}$$

#### C.1.5 Third-Degree Polynomial Equation for HVAC B

$$\begin{aligned}
EUI = & 161.194 + (16.663)*window\_u + (-15.206)*wall\_r + (-12.0518)*roof\_r + \\
& (241034)*infiltration + (3.44042)*lights + (15.0744)*equipment + (4.58402e+07)*dhw + \\
& (4.54075)*window\_u**2 + (-3.45571)*window\_u*wall\_r + (-0.127574)*window\_u*roof\_r + \\
& (35526.3)*window\_u*infiltration + (-1.24665)*window\_u*lights + (- \\
& 1.64148)*window\_u*equipment + (-2.72721e+06)*window\_u*dhw + (3.97052)*wall\_r**2 + \\
& (0.0147246)*wall\_r*roof\_r + (-34883.6)*wall\_r*infiltration + (0.269492)*wall\_r*lights \\
& + (1.23067)*wall\_r*equipment + (-1.44747e+06)*wall\_r*dhw + (2.38517)*roof\_r**2 + (- \\
& 11056.9)*roof\_r*infiltration + (-0.23166)*roof\_r*lights + (0.331789)*roof\_r*equipment \\
& + (-1.66719e+06)*roof\_r*dhw + (5.91237e+07)*infiltration**2 + (- \\
& 2276.01)*infiltration*lights + (-17093.9)*infiltration*equipment + \\
& (1.84519e+10)*infiltration*dhw + (0.242497)*lights**2 + (0.184563)*lights*equipment + \\
& (-767277)*lights*dhw + (0.325855)*equipment**2 + (1.57363e+06)*equipment*dhw + \\
& (4.568e+11)*dhw**2 + (-0.419858)*window\_u**3 + (0.140705)*window\_u**2*wall\_r + (- \\
& 0.0547617)*window\_u**2*roof\_r + (-2703.28)*window\_u**2*infiltration + \\
& (0.0516479)*window\_u**2*lights + (-0.016602)*window\_u**2*equipment + (- \\
& 79961)*window\_u**2*dhw + (0.18273)*window\_u*wall\_r**2 + \\
& (0.013112)*window\_u*wall\_r*roof\_r + (1279.83)*window\_u*wall\_r*infiltration + (- \\
& 0.00707522)*window\_u*wall\_r*lights + (0.0177508)*window\_u*wall\_r*equipment + (- \\
& 28709.8)*window\_u*wall\_r*dhw + (0.048433)*window\_u*roof\_r**2 + \\
& (505.424)*window\_u*roof\_r*infiltration + (-0.00279508)*window\_u*roof\_r*lights + (- \\
& 0.0293596)*window\_u*roof\_r*equipment + (-81453.4)*window\_u*roof\_r*dhw + (- \\
& 1.87178e+07)*window\_u*infiltration**2 + (654.371)*window\_u*infiltration*lights + \\
& (671.199)*window\_u*infiltration*equipment + (-3.74643e+07)*window\_u*infiltration*dhw \\
& + (0.00157723)*window\_u*lights**2 + (0.00499379)*window\_u*lights*equipment + \\
& (95372.6)*window\_u*lights*dhw + (0.0229184)*window\_u*equipment**2 + (- \\
& 24265.8)*window\_u*equipment*dhw + (4.15352e+11)*window\_u*dhw**2 + (-0.2832)*wall\_r**3 \\
& + (-0.0235099)*wall\_r**2*roof\_r + (2392.42)*wall\_r**2*infiltration + (- \\
& 0.0327746)*wall\_r**2*lights + (-0.0959801)*wall\_r**2*equipment + \\
& (115959)*wall\_r**2*dhw + (0.0030282)*wall\_r*roof\_r**2 + (-
\end{aligned}$$

$$\begin{aligned}
&171.666)*wall\_r*roof\_r*infiltration + (-0.00528735)*wall\_r*roof\_r*lights + \\
&(0.016366)*wall\_r*roof\_r*equipment + (18318)*wall\_r*roof\_r*dhw + \\
&(1.21304e+07)*wall\_r*infiltration**2 + (137.42)*wall\_r*infiltration*lights + (- \\
&544.312)*wall\_r*infiltration*equipment + (1.86598e+08)*wall\_r*infiltration*dhw + (- \\
&0.0101236)*wall\_r*lights**2 + (0.0092212)*wall\_r*lights*equipment + \\
&(28863)*wall\_r*lights*dhw + (-0.00656387)*wall\_r*equipment**2 + \\
&(5913.99)*wall\_r*equipment*dhw + (1.40165e+10)*wall\_r*dhw**2 + (-0.121765)*roof\_r**3 \\
&+ (461.498)*roof\_r**2*infiltration + (0.00266431)*roof\_r**2*lights + (- \\
&0.0210324)*roof\_r**2*equipment + (40483.6)*roof\_r**2*dhw + \\
&(7.69431e+06)*roof\_r*infiltration**2 + (-136.257)*roof\_r*infiltration*lights + (- \\
&270.86)*roof\_r*infiltration*equipment + (7.79999e+07)*roof\_r*infiltration*dhw + (- \\
&0.000775459)*roof\_r*lights**2 + (0.00321919)*roof\_r*lights*equipment + \\
&(68366.8)*roof\_r*lights*dhw + (0.00260799)*roof\_r*equipment**2 + \\
&(13677.7)*roof\_r*equipment*dhw + (4.93216e+10)*roof\_r*dhw**2 + (- \\
&8.42718e+10)*infiltration**3 + (3.77555e+06)*infiltration**2*lights + \\
&(1.26448e+07)*infiltration**2*equipment + (1.98861e+12)*infiltration**2*dhw + \\
&(23.4405)*infiltration*lights**2 + (-270.081)*infiltration*lights*equipment + (- \\
&5.50286e+08)*infiltration*lights*dhw + (1.66365)*infiltration*equipment**2 + (- \\
&5.14615e+08)*infiltration*equipment*dhw + (-1.36379e+15)*infiltration*dhw**2 + (- \\
&0.0147317)*lights**3 + (0.00296384)*lights**2*equipment + (19075.8)*lights**2*dhw + \\
&(-0.000453137)*lights*equipment**2 + (-14225.4)*lights*equipment*dhw + \\
&(2.06658e+10)*lights*dhw**2 + (-0.00315022)*equipment**3 + (3772.48)*equipment**2*dhw \\
&+ (-1.70122e+11)*equipment*dhw**2 + (7.57872e+16)*dhw**3
\end{aligned}$$

### C.1.6 Fourth-Degree Polynomial Equation for HVAC B

$$\begin{aligned}
EUI = &152.426 + (13.3442)*window\_u + (-18.7948)*wall\_r + (-16.6992)*roof\_r + \\
&(221300)*infiltration + (3.26331)*lights + (14.7945)*equipment + (5.82544e+07)*dhw + \\
&(4.79805)*window\_u**2 + (-6.79955)*window\_u*wall\_r + (-0.497305)*window\_u*roof\_r + \\
&(35535.5)*window\_u*infiltration + (-1.49598)*window\_u*lights + (- \\
&2.38377)*window\_u*equipment + (433748)*window\_u*dhw + (6.7325)*wall\_r**2 + (- \\
&1.34211)*wall\_r*roof\_r + (-24516.4)*wall\_r*infiltration + (-0.590251)*wall\_r*lights + \\
&(2.00031)*wall\_r*equipment + (-659096)*wall\_r*dhw + (4.93525)*roof\_r**2 + (- \\
&30080)*roof\_r*infiltration + (-0.16564)*roof\_r*lights + (0.808549)*roof\_r*equipment + \\
&(-3.56771e+06)*roof\_r*dhw + (-6.44963e+07)*infiltration**2 + \\
&(10447.3)*infiltration*lights + (-14698.3)*infiltration*equipment + \\
&(2.70367e+10)*infiltration*dhw + (0.20314)*lights**2 + (0.0476043)*lights*equipment + \\
&(-248304)*lights*dhw + (0.383372)*equipment**2 + (1.18718e+06)*equipment*dhw + (- \\
&3.24382e+11)*dhw**2 + (0.265199)*window\_u**3 + (0.988374)*window\_u**2*wall\_r + (- \\
&0.367346)*window\_u**2*roof\_r + (-7881.17)*window\_u**2*infiltration + (- \\
&0.174517)*window\_u**2*lights + (-0.119812)*window\_u**2*equipment + \\
&(265352)*window\_u**2*dhw + (1.23869)*window\_u*wall\_r**2 + (- \\
&0.0193121)*window\_u*wall\_r*roof\_r + (-2907.12)*window\_u*wall\_r*infiltration + \\
&(0.332387)*window\_u*wall\_r*lights + (0.125174)*window\_u*wall\_r*equipment + (- \\
&1.0909e+06)*window\_u*wall\_r*dhw + (0.0829673)*window\_u*roof\_r**2 + \\
&(4077.16)*window\_u*roof\_r*infiltration + (0.0759576)*window\_u*roof\_r*lights + (- \\
&0.273516)*window\_u*roof\_r*equipment + (622730)*window\_u*roof\_r*dhw + \\
&(3.5287e+07)*window\_u*infiltration**2 + (-1107.48)*window\_u*infiltration*lights + \\
&(2458.42)*window\_u*infiltration*equipment + (-3.21015e+09)*window\_u*infiltration*dhw \\
&+ (-0.0722401)*window\_u*lights**2 + (0.0370535)*window\_u*lights*equipment + \\
&(466238)*window\_u*lights*dhw + (0.0855382)*window\_u*equipment**2 + \\
&(30970.1)*window\_u*equipment*dhw + (-6.53069e+11)*window\_u*dhw**2 + (- \\
&1.34162)*wall\_r**3 + (0.0477131)*wall\_r**2*roof\_r + (11029.1)*wall\_r**2*infiltration \\
&+ (0.151101)*wall\_r**2*lights + (-0.363411)*wall\_r**2*equipment + \\
&(452229)*wall\_r**2*dhw + (-0.0510521)*wall\_r*roof\_r**2 + (- \\
&2395.39)*wall\_r*roof\_r*infiltration + (0.0460493)*wall\_r*roof\_r*lights +
\end{aligned}$$

(0.0775548)\*wall\_r\*roof\_r\*equipment + (733339)\*wall\_r\*roof\_r\*dhw +  
 (2.06775e+07)\*wall\_r\*infiltration\*\*2 + (-2595.86)\*wall\_r\*infiltration\*lights + (-  
 1178.48)\*wall\_r\*infiltration\*equipment + (-9.90612e+09)\*wall\_r\*infiltration\*dhw + (-  
 0.0368554)\*wall\_r\*lights\*\*2 + (0.0586026)\*wall\_r\*lights\*equipment + (-  
 34668.7)\*wall\_r\*lights\*dhw + (-0.0390558)\*wall\_r\*equipment\*\*2 +  
 (109924)\*wall\_r\*equipment\*dhw + (-2.21345e+11)\*wall\_r\*dhw\*\*2 + (-0.565192)\*roof\_r\*\*3  
 + (2606.07)\*roof\_r\*\*2\*infiltration + (0.0114795)\*roof\_r\*\*2\*lights + (-  
 0.0241025)\*roof\_r\*\*2\*equipment + (287271)\*roof\_r\*\*2\*dhw +  
 (5.14575e+07)\*roof\_r\*infiltration\*\*2 + (-231.081)\*roof\_r\*infiltration\*lights + (-  
 1455.81)\*roof\_r\*infiltration\*equipment + (1.76649e+09)\*roof\_r\*infiltration\*dhw + (-  
 0.0222865)\*roof\_r\*lights\*\*2 + (0.0387355)\*roof\_r\*lights\*equipment + (-  
 26168.6)\*roof\_r\*lights\*dhw + (0.00669152)\*roof\_r\*equipment\*\*2 + (-  
 118559)\*roof\_r\*equipment\*dhw + (4.48046e+10)\*roof\_r\*dhw\*\*2 +  
 (1.94967e+11)\*infiltration\*\*3 + (-5.12305e+06)\*infiltration\*\*2\*lights +  
 (1.34247e+07)\*infiltration\*\*2\*equipment + (-5.14663e+13)\*infiltration\*\*2\*dhw +  
 (187.738)\*infiltration\*lights\*\*2 + (-598.834)\*infiltration\*lights\*equipment + (-  
 1.30642e+09)\*infiltration\*lights\*dhw + (-129.697)\*infiltration\*equipment\*\*2 + (-  
 7.56057e+08)\*infiltration\*equipment\*dhw + (2.37428e+15)\*infiltration\*dhw\*\*2 + (-  
 0.00838117)\*lights\*\*3 + (-0.00913773)\*lights\*\*2\*equipment + (36912.6)\*lights\*\*2\*dhw +  
 (0.00340815)\*lights\*equipment\*\*2 + (-15209.9)\*lights\*equipment\*dhw + (-  
 5.4065e+10)\*lights\*dhw\*\*2 + (-2.28733e-06)\*equipment\*\*3 + (-28111.6)\*equipment\*\*2\*dhw  
 + (-4.99617e+10)\*equipment\*dhw\*\*2 + (-2.78468e+17)\*dhw\*\*3 + (-0.173656)\*window\_u\*\*4 +  
 (-0.106544)\*window\_u\*\*3\*wall\_r + (0.12395)\*window\_u\*\*3\*roof\_r + (-  
 358.448)\*window\_u\*\*3\*infiltration + (-0.0337978)\*window\_u\*\*3\*lights +  
 (0.0344661)\*window\_u\*\*3\*equipment + (72581.4)\*window\_u\*\*3\*dhw + (-  
 0.121555)\*window\_u\*\*2\*wall\_r\*\*2 + (-0.0134572)\*window\_u\*\*2\*wall\_r\*roof\_r +  
 (1909.56)\*window\_u\*\*2\*wall\_r\*infiltration + (-0.00667921)\*window\_u\*\*2\*wall\_r\*lights +  
 (-0.0229882)\*window\_u\*\*2\*wall\_r\*equipment + (51979.2)\*window\_u\*\*2\*wall\_r\*dhw +  
 (0.00991282)\*window\_u\*\*2\*roof\_r\*\*2 + (-9.59972)\*window\_u\*\*2\*roof\_r\*infiltration +  
 (0.0116849)\*window\_u\*\*2\*roof\_r\*lights + (-0.00154993)\*window\_u\*\*2\*roof\_r\*equipment +  
 (-129167)\*window\_u\*\*2\*roof\_r\*dhw + (-2.05209e+07)\*window\_u\*\*2\*infiltration\*\*2 +  
 (143.656)\*window\_u\*\*2\*infiltration\*lights +  
 (795.536)\*window\_u\*\*2\*infiltration\*equipment +  
 (1.35645e+09)\*window\_u\*\*2\*infiltration\*dhw + (0.0161695)\*window\_u\*\*2\*lights\*\*2 + (-  
 0.00783717)\*window\_u\*\*2\*lights\*equipment + (39203.2)\*window\_u\*\*2\*lights\*dhw + (-  
 0.00692193)\*window\_u\*\*2\*equipment\*\*2 + (-10872.9)\*window\_u\*\*2\*equipment\*dhw + (-  
 1.22704e+11)\*window\_u\*\*2\*dhw\*\*2 + (-0.0467411)\*window\_u\*wall\_r\*\*3 +  
 (0.0130126)\*window\_u\*wall\_r\*\*2\*roof\_r + (-826.103)\*window\_u\*wall\_r\*\*2\*infiltration +  
 (-0.00636486)\*window\_u\*wall\_r\*\*2\*lights + (0.00928424)\*window\_u\*wall\_r\*\*2\*equipment +  
 (32616.1)\*window\_u\*wall\_r\*\*2\*dhw + (-0.00609455)\*window\_u\*wall\_r\*roof\_r\*\*2 +  
 (35.7379)\*window\_u\*wall\_r\*roof\_r\*infiltration + (-  
 0.00582)\*window\_u\*wall\_r\*roof\_r\*lights + (-  
 0.00349892)\*window\_u\*wall\_r\*roof\_r\*equipment + (25850.3)\*window\_u\*wall\_r\*roof\_r\*dhw +  
 (9.15655e+06)\*window\_u\*wall\_r\*infiltration\*\*2 + (-  
 126.799)\*window\_u\*wall\_r\*infiltration\*lights + (-  
 641.589)\*window\_u\*wall\_r\*infiltration\*equipment +  
 (9.60142e+08)\*window\_u\*wall\_r\*infiltration\*dhw + (-  
 0.0099668)\*window\_u\*wall\_r\*lights\*\*2 + (-0.00227213)\*window\_u\*wall\_r\*lights\*equipment  
 + (464.094)\*window\_u\*wall\_r\*lights\*dhw + (0.00437415)\*window\_u\*wall\_r\*equipment\*\*2 +  
 (15550.8)\*window\_u\*wall\_r\*equipment\*dhw + (-1.56104e+10)\*window\_u\*wall\_r\*dhw\*\*2 + (-  
 0.00655357)\*window\_u\*roof\_r\*\*3 + (-321.702)\*window\_u\*roof\_r\*\*2\*infiltration +  
 (0.00132252)\*window\_u\*roof\_r\*\*2\*lights + (0.00401691)\*window\_u\*roof\_r\*\*2\*equipment +  
 (27033.4)\*window\_u\*roof\_r\*\*2\*dhw + (-662432)\*window\_u\*roof\_r\*infiltration\*\*2 +  
 (35.3199)\*window\_u\*roof\_r\*infiltration\*lights +  
 (44.4491)\*window\_u\*roof\_r\*infiltration\*equipment + (-

8.2957e+07)\*window\_u\*roof\_r\*infiltration\*dhw + (-  
 0.00299115)\*window\_u\*roof\_r\*lights\*\*2 + (0.00218882)\*window\_u\*roof\_r\*lights\*equipment  
 + (-31219.9)\*window\_u\*roof\_r\*lights\*dhw + (0.00468122)\*window\_u\*roof\_r\*equipment\*\*2 +  
 (18192.3)\*window\_u\*roof\_r\*equipment\*dhw + (-6.93187e+10)\*window\_u\*roof\_r\*dhw\*\*2 + (-  
 1.07961e+11)\*window\_u\*infiltration\*\*3 + (3.30889e+06)\*window\_u\*infiltration\*\*2\*lights  
 + (7.62847e+06)\*window\_u\*infiltration\*\*2\*equipment +  
 (2.2693e+12)\*window\_u\*infiltration\*\*2\*dhw + (37.3713)\*window\_u\*infiltration\*lights\*\*2  
 + (-129.78)\*window\_u\*infiltration\*lights\*equipment + (-  
 7.79576e+07)\*window\_u\*infiltration\*lights\*dhw + (-  
 239.237)\*window\_u\*infiltration\*equipment\*\*2 + (-  
 4.91467e+08)\*window\_u\*infiltration\*equipment\*dhw +  
 (5.28601e+13)\*window\_u\*infiltration\*dhw\*\*2 + (0.00391316)\*window\_u\*lights\*\*3 + (-  
 0.00281882)\*window\_u\*lights\*\*2\*equipment + (2233.44)\*window\_u\*lights\*\*2\*dhw +  
 (0.000978512)\*window\_u\*lights\*equipment\*\*2 + (11165.9)\*window\_u\*lights\*equipment\*dhw  
 + (-6.44689e+10)\*window\_u\*lights\*dhw\*\*2 + (-0.00111118)\*window\_u\*equipment\*\*3 +  
 (11538.7)\*window\_u\*equipment\*\*2\*dhw + (-4.12155e+10)\*window\_u\*equipment\*dhw\*\*2 +  
 (2.19223e+17)\*window\_u\*dhw\*\*3 + (0.0782694)\*wall\_r\*\*4 +  
 (0.000314008)\*wall\_r\*\*3\*roof\_r + (-709.508)\*wall\_r\*\*3\*infiltration + (-  
 0.00600632)\*wall\_r\*\*3\*lights + (0.0228189)\*wall\_r\*\*3\*equipment + (-  
 619.691)\*wall\_r\*\*3\*dhw + (0.00624293)\*wall\_r\*\*2\*roof\_r\*\*2 +  
 (78.0325)\*wall\_r\*\*2\*roof\_r\*infiltration + (-0.0103401)\*wall\_r\*\*2\*roof\_r\*lights + (-  
 0.00415876)\*wall\_r\*\*2\*roof\_r\*equipment + (-18708)\*wall\_r\*\*2\*roof\_r\*dhw + (-  
 3.46896e+06)\*wall\_r\*\*2\*infiltration\*\*2 + (78.0675)\*wall\_r\*\*2\*infiltration\*lights +  
 (182.26)\*wall\_r\*\*2\*infiltration\*equipment + (2.15929e+08)\*wall\_r\*\*2\*infiltration\*dhw  
 + (0.00294757)\*wall\_r\*\*2\*lights\*\*2 + (-0.00321585)\*wall\_r\*\*2\*lights\*equipment + (-  
 12954.8)\*wall\_r\*\*2\*lights\*dhw + (-0.000348188)\*wall\_r\*\*2\*equipment\*\*2 + (-  
 6812.55)\*wall\_r\*\*2\*equipment\*dhw + (-2.79576e+10)\*wall\_r\*\*2\*dhw\*\*2 + (9.88328e-  
 06)\*wall\_r\*roof\_r\*\*3 + (89.6216)\*wall\_r\*roof\_r\*\*2\*infiltration +  
 (0.00028104)\*wall\_r\*roof\_r\*\*2\*lights + (-0.000100378)\*wall\_r\*roof\_r\*\*2\*equipment + (-  
 9010.86)\*wall\_r\*roof\_r\*\*2\*dhw + (768065)\*wall\_r\*roof\_r\*infiltration\*\*2 +  
 (68.2674)\*wall\_r\*roof\_r\*infiltration\*lights + (-  
 7.51292)\*wall\_r\*roof\_r\*infiltration\*equipment + (-  
 1.25303e+08)\*wall\_r\*roof\_r\*infiltration\*dhw + (0.0023029)\*wall\_r\*roof\_r\*lights\*\*2 +  
 (-0.000839486)\*wall\_r\*roof\_r\*lights\*equipment + (-3497.87)\*wall\_r\*roof\_r\*lights\*dhw +  
 (-0.000921378)\*wall\_r\*roof\_r\*equipment\*\*2 + (709.846)\*wall\_r\*roof\_r\*equipment\*dhw +  
 (-5.34645e+10)\*wall\_r\*roof\_r\*dhw\*\*2 + (2.04099e+10)\*wall\_r\*infiltration\*\*3 +  
 (529378)\*wall\_r\*infiltration\*\*2\*lights + (-  
 2.60079e+06)\*wall\_r\*infiltration\*\*2\*equipment + (-  
 1.1138e+12)\*wall\_r\*infiltration\*\*2\*dhw + (-23.4675)\*wall\_r\*infiltration\*lights\*\*2 +  
 (59.3642)\*wall\_r\*infiltration\*lights\*equipment +  
 (2.29449e+08)\*wall\_r\*infiltration\*lights\*dhw +  
 (104.077)\*wall\_r\*infiltration\*equipment\*\*2 + (-  
 2.90837e+07)\*wall\_r\*infiltration\*equipment\*dhw +  
 (7.31989e+14)\*wall\_r\*infiltration\*dhw\*\*2 + (0.00271114)\*wall\_r\*lights\*\*3 + (-  
 0.000180234)\*wall\_r\*lights\*\*2\*equipment + (-5931.45)\*wall\_r\*lights\*\*2\*dhw + (-  
 0.000773166)\*wall\_r\*lights\*equipment\*\*2 + (-4330.17)\*wall\_r\*lights\*equipment\*dhw +  
 (3.0194e+10)\*wall\_r\*lights\*dhw\*\*2 + (-0.000420713)\*wall\_r\*equipment\*\*3 +  
 (4003.06)\*wall\_r\*equipment\*\*2\*dhw + (-1.68238e+10)\*wall\_r\*equipment\*dhw\*\*2 +  
 (3.21562e+16)\*wall\_r\*dhw\*\*3 + (0.0226937)\*roof\_r\*\*4 + (-  
 73.4497)\*roof\_r\*\*3\*infiltration + (-0.00133626)\*roof\_r\*\*3\*lights +  
 (0.00202549)\*roof\_r\*\*3\*equipment + (-11515.4)\*roof\_r\*\*3\*dhw + (-  
 1.03114e+06)\*roof\_r\*\*2\*infiltration\*\*2 + (23.7495)\*roof\_r\*\*2\*infiltration\*lights +  
 (10.2116)\*roof\_r\*\*2\*infiltration\*equipment + (-  
 3.16656e+07)\*roof\_r\*\*2\*infiltration\*dhw + (0.000648853)\*roof\_r\*\*2\*lights\*\*2 +  
 (1.1652e-05)\*roof\_r\*\*2\*lights\*equipment + (-1931.79)\*roof\_r\*\*2\*lights\*dhw + (-

$$\begin{aligned}
& 0.00116001) * \text{roof\_r}^{**2} * \text{equipment}^{**2} + (-2780.93) * \text{roof\_r}^{**2} * \text{equipment} * \text{dhw} + (- \\
& 4.45049\text{e}+09) * \text{roof\_r}^{**2} * \text{dhw}^{**2} + (-3.39149\text{e}+10) * \text{roof\_r} * \text{infiltration}^{**3} + \\
& (109502) * \text{roof\_r} * \text{infiltration}^{**2} * \text{lights} + (317938) * \text{roof\_r} * \text{infiltration}^{**2} * \text{equipment} + \\
& (-1.05213\text{e}+12) * \text{roof\_r} * \text{infiltration}^{**2} * \text{dhw} + (-44.8364) * \text{roof\_r} * \text{infiltration} * \text{lights}^{**2} \\
& + (5.30209) * \text{roof\_r} * \text{infiltration} * \text{lights} * \text{equipment} + (- \\
& 1.0908\text{e}+07) * \text{roof\_r} * \text{infiltration} * \text{lights} * \text{dhw} + \\
& (0.617871) * \text{roof\_r} * \text{infiltration} * \text{equipment}^{**2} + \\
& (1.74336\text{e}+08) * \text{roof\_r} * \text{infiltration} * \text{equipment} * \text{dhw} + (- \\
& 2.59371\text{e}+14) * \text{roof\_r} * \text{infiltration} * \text{dhw}^{**2} + (0.00036404) * \text{roof\_r} * \text{lights}^{**3} + (- \\
& 0.000415135) * \text{roof\_r} * \text{lights}^{**2} * \text{equipment} + (6254.71) * \text{roof\_r} * \text{lights}^{**2} * \text{dhw} + (- \\
& 0.000552105) * \text{roof\_r} * \text{lights} * \text{equipment}^{**2} + (-4825.93) * \text{roof\_r} * \text{lights} * \text{equipment} * \text{dhw} + \\
& (1.50548\text{e}+10) * \text{roof\_r} * \text{lights} * \text{dhw}^{**2} + (-1.81609\text{e}-05) * \text{roof\_r} * \text{equipment}^{**3} + \\
& (1739.25) * \text{roof\_r} * \text{equipment}^{**2} * \text{dhw} + (4.71587\text{e}+09) * \text{roof\_r} * \text{equipment} * \text{dhw}^{**2} + \\
& (2.69678\text{e}+16) * \text{roof\_r} * \text{dhw}^{**3} + (-2.72143\text{e}+14) * \text{infiltration}^{**4} + (- \\
& 7.71119\text{e}+09) * \text{infiltration}^{**3} * \text{lights} + (2.59076\text{e}+10) * \text{infiltration}^{**3} * \text{equipment} + \\
& (5.34593\text{e}+16) * \text{infiltration}^{**3} * \text{dhw} + (251613) * \text{infiltration}^{**2} * \text{lights}^{**2} + \\
& (24811.8) * \text{infiltration}^{**2} * \text{lights} * \text{equipment} + (1.18982\text{e}+12) * \text{infiltration}^{**2} * \text{lights} * \text{dhw} \\
& + (-1.8439\text{e}+06) * \text{infiltration}^{**2} * \text{equipment}^{**2} + \\
& (7.77189\text{e}+11) * \text{infiltration}^{**2} * \text{equipment} * \text{dhw} + (-1.46802\text{e}+18) * \text{infiltration}^{**2} * \text{dhw}^{**2} + \\
& (10.0916) * \text{infiltration} * \text{lights}^{**3} + (20.4549) * \text{infiltration} * \text{lights}^{**2} * \text{equipment} + (- \\
& 1.3402\text{e}+08) * \text{infiltration} * \text{lights}^{**2} * \text{dhw} + (13.9481) * \text{infiltration} * \text{lights} * \text{equipment}^{**2} + \\
& (-4.20469\text{e}+07) * \text{infiltration} * \text{lights} * \text{equipment} * \text{dhw} + \\
& (1.86539\text{e}+14) * \text{infiltration} * \text{lights} * \text{dhw}^{**2} + (38.3632) * \text{infiltration} * \text{equipment}^{**3} + \\
& (2.75128\text{e}+07) * \text{infiltration} * \text{equipment}^{**2} * \text{dhw} + (- \\
& 4.52927\text{e}+13) * \text{infiltration} * \text{equipment} * \text{dhw}^{**2} + (-1.14145\text{e}+20) * \text{infiltration} * \text{dhw}^{**3} + \\
& (0.000264118) * \text{lights}^{**4} + (-0.000358541) * \text{lights}^{**3} * \text{equipment} + (- \\
& 4687.39) * \text{lights}^{**3} * \text{dhw} + (-9.67112\text{e}-05) * \text{lights}^{**2} * \text{equipment}^{**2} + \\
& (5116.71) * \text{lights}^{**2} * \text{equipment} * \text{dhw} + (4.0637\text{e}+09) * \text{lights}^{**2} * \text{dhw}^{**2} + (1.577\text{e}- \\
& 05) * \text{lights} * \text{equipment}^{**3} + (-967.328) * \text{lights} * \text{equipment}^{**2} * \text{dhw} + \\
& (4.14906\text{e}+08) * \text{lights} * \text{equipment} * \text{dhw}^{**2} + (-9.0676\text{e}+15) * \text{lights} * \text{dhw}^{**3} + (- \\
& 0.000323259) * \text{equipment}^{**4} + (792.32) * \text{equipment}^{**3} * \text{dhw} + (- \\
& 7.638\text{e}+09) * \text{equipment}^{**2} * \text{dhw}^{**2} + (2.49793\text{e}+16) * \text{equipment} * \text{dhw}^{**3} + (- \\
& 8.73744\text{e}+21) * \text{dhw}^{**4}
\end{aligned}$$

### C.1.7 Second-Degree Polynomial Equation for HVAC C

$$\begin{aligned}
\text{EUI} = & 152.426 + (13.3442) * \text{window\_u} + (-18.7948) * \text{wall\_r} + (-16.6992) * \text{roof\_r} + \\
& (221300) * \text{infiltration} + (3.26331) * \text{lights} + (14.7945) * \text{equipment} + (5.82544\text{e}+07) * \text{dhw} + \\
& (4.79805) * \text{window\_u}^{**2} + (-6.79955) * \text{window\_u} * \text{wall\_r} + (-0.497305) * \text{window\_u} * \text{roof\_r} + \\
& (35535.5) * \text{window\_u} * \text{infiltration} + (-1.49598) * \text{window\_u} * \text{lights} + (- \\
& 2.38377) * \text{window\_u} * \text{equipment} + (433748) * \text{window\_u} * \text{dhw} + (6.7325) * \text{wall\_r}^{**2} + (- \\
& 1.34211) * \text{wall\_r} * \text{roof\_r} + (-24516.4) * \text{wall\_r} * \text{infiltration} + (-0.590251) * \text{wall\_r} * \text{lights} + \\
& (2.00031) * \text{wall\_r} * \text{equipment} + (-659096) * \text{wall\_r} * \text{dhw} + (4.93525) * \text{roof\_r}^{**2} + (- \\
& 30080) * \text{roof\_r} * \text{infiltration} + (-0.16564) * \text{roof\_r} * \text{lights} + (0.808549) * \text{roof\_r} * \text{equipment} + \\
& (-3.56771\text{e}+06) * \text{roof\_r} * \text{dhw} + (-6.44963\text{e}+07) * \text{infiltration}^{**2} + \\
& (10447.3) * \text{infiltration} * \text{lights} + (-14698.3) * \text{infiltration} * \text{equipment} + \\
& (2.70367\text{e}+10) * \text{infiltration} * \text{dhw} + (0.20314) * \text{lights}^{**2} + (0.0476043) * \text{lights} * \text{equipment} + \\
& (-248304) * \text{lights} * \text{dhw} + (0.383372) * \text{equipment}^{**2} + (1.18718\text{e}+06) * \text{equipment} * \text{dhw} + (- \\
& 3.24382\text{e}+11) * \text{dhw}^{**2} + (0.265199) * \text{window\_u}^{**3} + (0.988374) * \text{window\_u}^{**2} * \text{wall\_r} + (- \\
& 0.367346) * \text{window\_u}^{**2} * \text{roof\_r} + (-7881.17) * \text{window\_u}^{**2} * \text{infiltration} + (- \\
& 0.174517) * \text{window\_u}^{**2} * \text{lights} + (-0.119812) * \text{window\_u}^{**2} * \text{equipment} + \\
& (265352) * \text{window\_u}^{**2} * \text{dhw} + (1.23869) * \text{window\_u} * \text{wall\_r}^{**2} + (- \\
& 0.0193121) * \text{window\_u} * \text{wall\_r} * \text{roof\_r} + (-2907.12) * \text{window\_u} * \text{wall\_r} * \text{infiltration} + \\
& (0.332387) * \text{window\_u} * \text{wall\_r} * \text{lights} + (0.125174) * \text{window\_u} * \text{wall\_r} * \text{equipment} + (- \\
& 1.0909\text{e}+06) * \text{window\_u} * \text{wall\_r} * \text{dhw} + (0.0829673) * \text{window\_u} * \text{roof\_r}^{**2} + \\
& (4077.16) * \text{window\_u} * \text{roof\_r} * \text{infiltration} + (0.0759576) * \text{window\_u} * \text{roof\_r} * \text{lights} + (-
\end{aligned}$$

0.273516)\*window\_u\*roof\_r\*equipment + (622730)\*window\_u\*roof\_r\*dhw +  
 (3.5287e+07)\*window\_u\*infiltration\*\*2 + (-1107.48)\*window\_u\*infiltration\*lights +  
 (2458.42)\*window\_u\*infiltration\*equipment + (-3.21015e+09)\*window\_u\*infiltration\*dhw  
 + (-0.0722401)\*window\_u\*lights\*\*2 + (0.0370535)\*window\_u\*lights\*equipment +  
 (466238)\*window\_u\*lights\*dhw + (0.0855382)\*window\_u\*equipment\*\*2 +  
 (30970.1)\*window\_u\*equipment\*dhw + (-6.53069e+11)\*window\_u\*dhw\*\*2 + (-  
 1.34162)\*wall\_r\*\*3 + (0.0477131)\*wall\_r\*\*2\*roof\_r + (11029.1)\*wall\_r\*\*2\*infiltration  
 + (0.151101)\*wall\_r\*\*2\*lights + (-0.363411)\*wall\_r\*\*2\*equipment +  
 (452229)\*wall\_r\*\*2\*dhw + (-0.0510521)\*wall\_r\*roof\_r\*\*2 + (-  
 2395.39)\*wall\_r\*roof\_r\*infiltration + (0.0460493)\*wall\_r\*roof\_r\*lights +  
 (0.0775548)\*wall\_r\*roof\_r\*equipment + (733339)\*wall\_r\*roof\_r\*dhw +  
 (2.06775e+07)\*wall\_r\*infiltration\*\*2 + (-2595.86)\*wall\_r\*infiltration\*lights + (-  
 1178.48)\*wall\_r\*infiltration\*equipment + (-9.90612e+09)\*wall\_r\*infiltration\*dhw + (-  
 0.0368554)\*wall\_r\*lights\*\*2 + (0.0586026)\*wall\_r\*lights\*equipment + (-  
 34668.7)\*wall\_r\*lights\*dhw + (-0.0390558)\*wall\_r\*equipment\*\*2 +  
 (109924)\*wall\_r\*equipment\*dhw + (-2.21345e+11)\*wall\_r\*dhw\*\*2 + (-0.565192)\*roof\_r\*\*3  
 + (2606.07)\*roof\_r\*\*2\*infiltration + (0.0114795)\*roof\_r\*\*2\*lights + (-  
 0.0241025)\*roof\_r\*\*2\*equipment + (287271)\*roof\_r\*\*2\*dhw +  
 (5.14575e+07)\*roof\_r\*infiltration\*\*2 + (-231.081)\*roof\_r\*infiltration\*lights + (-  
 1455.81)\*roof\_r\*infiltration\*equipment + (1.76649e+09)\*roof\_r\*infiltration\*dhw + (-  
 0.0222865)\*roof\_r\*lights\*\*2 + (0.0387355)\*roof\_r\*lights\*equipment + (-  
 26168.6)\*roof\_r\*lights\*dhw + (0.00669152)\*roof\_r\*equipment\*\*2 + (-  
 118559)\*roof\_r\*equipment\*dhw + (4.48046e+10)\*roof\_r\*dhw\*\*2 +  
 (1.94967e+11)\*infiltration\*\*3 + (-5.12305e+06)\*infiltration\*\*2\*lights +  
 (1.34247e+07)\*infiltration\*\*2\*equipment + (-5.14663e+13)\*infiltration\*\*2\*dhw +  
 (187.738)\*infiltration\*lights\*\*2 + (-598.834)\*infiltration\*lights\*equipment + (-  
 1.30642e+09)\*infiltration\*lights\*dhw + (-129.697)\*infiltration\*equipment\*\*2 + (-  
 7.56057e+08)\*infiltration\*equipment\*dhw + (2.37428e+15)\*infiltration\*dhw\*\*2 + (-  
 0.00838117)\*lights\*\*3 + (-0.00913773)\*lights\*\*2\*equipment + (36912.6)\*lights\*\*2\*dhw +  
 (0.00340815)\*lights\*equipment\*\*2 + (-15209.9)\*lights\*equipment\*dhw + (-  
 5.4065e+10)\*lights\*dhw\*\*2 + (-2.28733e-06)\*equipment\*\*3 + (-28111.6)\*equipment\*\*2\*dhw  
 + (-4.99617e+10)\*equipment\*dhw\*\*2 + (-2.78468e+17)\*dhw\*\*3 + (-0.173656)\*window\_u\*\*4 +  
 (-0.106544)\*window\_u\*\*3\*wall\_r + (0.12395)\*window\_u\*\*3\*roof\_r + (-  
 358.448)\*window\_u\*\*3\*infiltration + (-0.0337978)\*window\_u\*\*3\*lights +  
 (0.0344661)\*window\_u\*\*3\*equipment + (72581.4)\*window\_u\*\*3\*dhw + (-  
 0.121555)\*window\_u\*\*2\*wall\_r\*\*2 + (-0.0134572)\*window\_u\*\*2\*wall\_r\*roof\_r +  
 (1909.56)\*window\_u\*\*2\*wall\_r\*infiltration + (-0.00667921)\*window\_u\*\*2\*wall\_r\*lights +  
 (-0.0229882)\*window\_u\*\*2\*wall\_r\*equipment + (51979.2)\*window\_u\*\*2\*wall\_r\*dhw +  
 (0.00991282)\*window\_u\*\*2\*roof\_r\*\*2 + (-9.59972)\*window\_u\*\*2\*roof\_r\*infiltration +  
 (0.0116849)\*window\_u\*\*2\*roof\_r\*lights + (-0.00154993)\*window\_u\*\*2\*roof\_r\*equipment +  
 (-129167)\*window\_u\*\*2\*roof\_r\*dhw + (-2.05209e+07)\*window\_u\*\*2\*infiltration\*\*2 +  
 (143.656)\*window\_u\*\*2\*infiltration\*lights +  
 (795.536)\*window\_u\*\*2\*infiltration\*equipment +  
 (1.35645e+09)\*window\_u\*\*2\*infiltration\*dhw + (0.0161695)\*window\_u\*\*2\*lights\*\*2 + (-  
 0.00783717)\*window\_u\*\*2\*lights\*equipment + (39203.2)\*window\_u\*\*2\*lights\*dhw + (-  
 0.00692193)\*window\_u\*\*2\*equipment\*\*2 + (-10872.9)\*window\_u\*\*2\*equipment\*dhw + (-  
 1.22704e+11)\*window\_u\*\*2\*dhw\*\*2 + (-0.0467411)\*window\_u\*wall\_r\*\*3 +  
 (0.0130126)\*window\_u\*wall\_r\*\*2\*roof\_r + (-826.103)\*window\_u\*wall\_r\*\*2\*infiltration +  
 (-0.00636486)\*window\_u\*wall\_r\*\*2\*lights + (0.00928424)\*window\_u\*wall\_r\*\*2\*equipment +  
 (32616.1)\*window\_u\*wall\_r\*\*2\*dhw + (-0.00609455)\*window\_u\*wall\_r\*roof\_r\*\*2 +  
 (35.7379)\*window\_u\*wall\_r\*roof\_r\*infiltration + (-  
 0.00582)\*window\_u\*wall\_r\*roof\_r\*lights + (-  
 0.00349892)\*window\_u\*wall\_r\*roof\_r\*equipment + (25850.3)\*window\_u\*wall\_r\*roof\_r\*dhw +  
 (9.15655e+06)\*window\_u\*wall\_r\*infiltration\*\*2 + (-  
 126.799)\*window\_u\*wall\_r\*infiltration\*lights + (-

641.589)\*window\_u\*wall\_r\*infiltration\*equipment +  
 (9.60142e+08)\*window\_u\*wall\_r\*infiltration\*dhw + (-  
 0.0099668)\*window\_u\*wall\_r\*lights\*\*2 + (-0.00227213)\*window\_u\*wall\_r\*lights\*equipment  
 + (464.094)\*window\_u\*wall\_r\*lights\*dhw + (0.00437415)\*window\_u\*wall\_r\*equipment\*\*2 +  
 (15550.8)\*window\_u\*wall\_r\*equipment\*dhw + (-1.56104e+10)\*window\_u\*wall\_r\*dhw\*\*2 + (-  
 0.00655357)\*window\_u\*roof\_r\*\*3 + (-321.702)\*window\_u\*roof\_r\*\*2\*infiltration +  
 (0.00132252)\*window\_u\*roof\_r\*\*2\*lights + (0.00401691)\*window\_u\*roof\_r\*\*2\*equipment +  
 (27033.4)\*window\_u\*roof\_r\*\*2\*dhw + (-662432)\*window\_u\*roof\_r\*infiltration\*\*2 +  
 (35.3199)\*window\_u\*roof\_r\*infiltration\*lights +  
 (44.4491)\*window\_u\*roof\_r\*infiltration\*equipment + (-  
 8.2957e+07)\*window\_u\*roof\_r\*infiltration\*dhw + (-  
 0.00299115)\*window\_u\*roof\_r\*lights\*\*2 + (0.00218882)\*window\_u\*roof\_r\*lights\*equipment  
 + (-31219.9)\*window\_u\*roof\_r\*lights\*dhw + (0.00468122)\*window\_u\*roof\_r\*equipment\*\*2 +  
 (18192.3)\*window\_u\*roof\_r\*equipment\*dhw + (-6.93187e+10)\*window\_u\*roof\_r\*dhw\*\*2 + (-  
 1.07961e+11)\*window\_u\*infiltration\*\*3 + (3.30889e+06)\*window\_u\*infiltration\*\*2\*lights  
 + (7.62847e+06)\*window\_u\*infiltration\*\*2\*equipment +  
 (2.2693e+12)\*window\_u\*infiltration\*\*2\*dhw + (37.3713)\*window\_u\*infiltration\*lights\*\*2  
 + (-129.78)\*window\_u\*infiltration\*lights\*equipment + (-  
 7.79576e+07)\*window\_u\*infiltration\*lights\*dhw + (-  
 239.237)\*window\_u\*infiltration\*equipment\*\*2 + (-  
 4.91467e+08)\*window\_u\*infiltration\*equipment\*dhw +  
 (5.28601e+13)\*window\_u\*infiltration\*dhw\*\*2 + (0.00391316)\*window\_u\*lights\*\*3 + (-  
 0.00281882)\*window\_u\*lights\*\*2\*equipment + (2233.44)\*window\_u\*lights\*\*2\*dhw +  
 (0.000978512)\*window\_u\*lights\*equipment\*\*2 + (11165.9)\*window\_u\*lights\*equipment\*dhw  
 + (-6.44689e+10)\*window\_u\*lights\*dhw\*\*2 + (-0.00111118)\*window\_u\*equipment\*\*3 +  
 (11538.7)\*window\_u\*equipment\*\*2\*dhw + (-4.12155e+10)\*window\_u\*equipment\*dhw\*\*2 +  
 (2.19223e+17)\*window\_u\*dhw\*\*3 + (0.0782694)\*wall\_r\*\*4 +  
 (0.000314008)\*wall\_r\*\*3\*roof\_r + (-709.508)\*wall\_r\*\*3\*infiltration + (-  
 0.00600632)\*wall\_r\*\*3\*lights + (0.0228189)\*wall\_r\*\*3\*equipment + (-  
 619.691)\*wall\_r\*\*3\*dhw + (0.00624293)\*wall\_r\*\*2\*roof\_r\*\*2 +  
 (78.0325)\*wall\_r\*\*2\*roof\_r\*infiltration + (-0.0103401)\*wall\_r\*\*2\*roof\_r\*lights + (-  
 0.00415876)\*wall\_r\*\*2\*roof\_r\*equipment + (-18708)\*wall\_r\*\*2\*roof\_r\*dhw + (-  
 3.46896e+06)\*wall\_r\*\*2\*infiltration\*\*2 + (78.0675)\*wall\_r\*\*2\*infiltration\*lights +  
 (182.26)\*wall\_r\*\*2\*infiltration\*equipment + (2.15929e+08)\*wall\_r\*\*2\*infiltration\*dhw  
 + (0.00294757)\*wall\_r\*\*2\*lights\*\*2 + (-0.00321585)\*wall\_r\*\*2\*lights\*equipment + (-  
 12954.8)\*wall\_r\*\*2\*lights\*dhw + (-0.000348188)\*wall\_r\*\*2\*equipment\*\*2 + (-  
 6812.55)\*wall\_r\*\*2\*equipment\*dhw + (-2.79576e+10)\*wall\_r\*\*2\*dhw\*\*2 + (9.88328e-  
 06)\*wall\_r\*roof\_r\*\*3 + (89.6216)\*wall\_r\*roof\_r\*\*2\*infiltration +  
 (0.00028104)\*wall\_r\*roof\_r\*\*2\*lights + (-0.000100378)\*wall\_r\*roof\_r\*\*2\*equipment + (-  
 9010.86)\*wall\_r\*roof\_r\*\*2\*dhw + (768065)\*wall\_r\*roof\_r\*infiltration\*\*2 +  
 (68.2674)\*wall\_r\*roof\_r\*infiltration\*lights + (-  
 7.51292)\*wall\_r\*roof\_r\*infiltration\*equipment + (-  
 1.25303e+08)\*wall\_r\*roof\_r\*infiltration\*dhw + (0.0023029)\*wall\_r\*roof\_r\*lights\*\*2 +  
 (-0.000839486)\*wall\_r\*roof\_r\*lights\*equipment + (-3497.87)\*wall\_r\*roof\_r\*lights\*dhw +  
 (-0.000921378)\*wall\_r\*roof\_r\*equipment\*\*2 + (709.846)\*wall\_r\*roof\_r\*equipment\*dhw +  
 (-5.34645e+10)\*wall\_r\*roof\_r\*dhw\*\*2 + (2.04099e+10)\*wall\_r\*infiltration\*\*3 +  
 (529378)\*wall\_r\*infiltration\*\*2\*lights + (-  
 2.60079e+06)\*wall\_r\*infiltration\*\*2\*equipment + (-  
 1.1138e+12)\*wall\_r\*infiltration\*\*2\*dhw + (-23.4675)\*wall\_r\*infiltration\*lights\*\*2 +  
 (59.3642)\*wall\_r\*infiltration\*lights\*equipment +  
 (2.29449e+08)\*wall\_r\*infiltration\*lights\*dhw +  
 (104.077)\*wall\_r\*infiltration\*equipment\*\*2 + (-  
 2.90837e+07)\*wall\_r\*infiltration\*equipment\*dhw +  
 (7.31989e+14)\*wall\_r\*infiltration\*dhw\*\*2 + (0.00271114)\*wall\_r\*lights\*\*3 + (-  
 0.000180234)\*wall\_r\*lights\*\*2\*equipment + (-5931.45)\*wall\_r\*lights\*\*2\*dhw + (-

$$\begin{aligned}
&0.000773166)*wall\_r*lights*equipment**2 + (-4330.17)*wall\_r*lights*equipment*dhw + \\
&(3.0194e+10)*wall\_r*lights*dhw**2 + (-0.000420713)*wall\_r*equipment**3 + \\
&(4003.06)*wall\_r*equipment**2*dhw + (-1.68238e+10)*wall\_r*equipment*dhw**2 + \\
&(3.21562e+16)*wall\_r*dhw**3 + (0.0226937)*roof\_r**4 + (- \\
&73.4497)*roof\_r**3*infiltration + (-0.00133626)*roof\_r**3*lights + \\
&(0.00202549)*roof\_r**3*equipment + (-11515.4)*roof\_r**3*dhw + (- \\
&1.03114e+06)*roof\_r**2*infiltration**2 + (23.7495)*roof\_r**2*infiltration*lights + \\
&(10.2116)*roof\_r**2*infiltration*equipment + (- \\
&3.16656e+07)*roof\_r**2*infiltration*dhw + (0.000648853)*roof\_r**2*lights**2 + \\
&(1.1652e-05)*roof\_r**2*lights*equipment + (-1931.79)*roof\_r**2*lights*dhw + (- \\
&0.00116001)*roof\_r**2*equipment**2 + (-2780.93)*roof\_r**2*equipment*dhw + (- \\
&4.45049e+09)*roof\_r**2*dhw**2 + (-3.39149e+10)*roof\_r*infiltration**3 + \\
&(109502)*roof\_r*infiltration**2*lights + (317938)*roof\_r*infiltration**2*equipment + \\
&(-1.05213e+12)*roof\_r*infiltration**2*dhw + (-44.8364)*roof\_r*infiltration*lights**2 \\
&+ (5.30209)*roof\_r*infiltration*lights*equipment + (- \\
&1.0908e+07)*roof\_r*infiltration*lights*dhw + \\
&(0.617871)*roof\_r*infiltration*equipment**2 + \\
&(1.74336e+08)*roof\_r*infiltration*equipment*dhw + (- \\
&2.59371e+14)*roof\_r*infiltration*dhw**2 + (0.00036404)*roof\_r*lights**3 + (- \\
&0.000415135)*roof\_r*lights**2*equipment + (6254.71)*roof\_r*lights**2*dhw + (- \\
&0.000552105)*roof\_r*lights*equipment**2 + (-4825.93)*roof\_r*lights*equipment*dhw + \\
&(1.50548e+10)*roof\_r*lights*dhw**2 + (-1.81609e-05)*roof\_r*equipment**3 + \\
&(1739.25)*roof\_r*equipment**2*dhw + (4.71587e+09)*roof\_r*equipment*dhw**2 + \\
&(2.69678e+16)*roof\_r*dhw**3 + (-2.72143e+14)*infiltration**4 + (- \\
&7.71119e+09)*infiltration**3*lights + (2.59076e+10)*infiltration**3*equipment + \\
&(5.34593e+16)*infiltration**3*dhw + (251613)*infiltration**2*lights**2 + \\
&(24811.8)*infiltration**2*lights*equipment + (1.18982e+12)*infiltration**2*lights*dhw \\
&+ (-1.8439e+06)*infiltration**2*equipment**2 + \\
&(7.77189e+11)*infiltration**2*equipment*dhw + (-1.46802e+18)*infiltration**2*dhw**2 + \\
&(10.0916)*infiltration*lights**3 + (20.4549)*infiltration*lights**2*equipment + (- \\
&1.3402e+08)*infiltration*lights**2*dhw + (13.9481)*infiltration*lights*equipment**2 + \\
&(-4.20469e+07)*infiltration*lights*equipment*dhw + \\
&(1.86539e+14)*infiltration*lights*dhw**2 + (38.3632)*infiltration*equipment**3 + \\
&(2.75128e+07)*infiltration*equipment**2*dhw + (- \\
&4.52927e+13)*infiltration*equipment*dhw**2 + (-1.14145e+20)*infiltration*dhw**3 + \\
&(0.000264118)*lights**4 + (-0.000358541)*lights**3*equipment + (- \\
&4687.39)*lights**3*dhw + (-9.67112e-05)*lights**2*equipment**2 + \\
&(5116.71)*lights**2*equipment*dhw + (4.0637e+09)*lights**2*dhw**2 + (1.577e- \\
&05)*lights*equipment**3 + (-967.328)*lights*equipment**2*dhw + \\
&(4.14906e+08)*lights*equipment*dhw**2 + (-9.0676e+15)*lights*dhw**3 + (- \\
&0.000323259)*equipment**4 + (792.32)*equipment**3*dhw + (- \\
&7.638e+09)*equipment**2*dhw**2 + (2.49793e+16)*equipment*dhw**3 + (- \\
&8.73744e+21)*dhw**4
\end{aligned}$$

### C.1.8 Third-Degree Polynomial Equation for HVAC C

$$\begin{aligned}
EUI = &288.121 + (17.9134)*window\_u + (-28.5149)*wall\_r + (-24.8666)*roof\_r + \\
&(167193)*infiltration + (-0.538381)*lights + (12.733)*equipment + (3.55171e+07)*dhw + \\
&(-0.999784)*window\_u**2 + (-1.86071)*window\_u*wall\_r + (0.88499)*window\_u*roof\_r + \\
&(8338.53)*window\_u*infiltration + (-0.531082)*window\_u*lights + (- \\
&0.800711)*window\_u*equipment + (2.08593e+06)*window\_u*dhw + (5.61317)*wall\_r**2 + \\
&(0.0696388)*wall\_r*roof\_r + (-12476.3)*wall\_r*infiltration + (0.515345)*wall\_r*lights \\
&+ (0.663822)*wall\_r*equipment + (-1.80881e+06)*wall\_r*dhw + (3.12048)*roof\_r**2 + \\
&(5424.32)*roof\_r*infiltration + (-0.00888858)*roof\_r*lights + (- \\
&0.0540741)*roof\_r*equipment + (321267)*roof\_r*dhw + (3.27649e+07)*infiltration**2 + \\
&(-871.153)*infiltration*lights + (-1240.77)*infiltration*equipment +
\end{aligned}$$

$$\begin{aligned}
& (2.37712e+10)*infiltration*dhw + (0.0483775)*lights**2 + (0.133667)*lights*equipment \\
& + (463443)*lights*dhw + (0.208037)*equipment**2 + (569018)*equipment*dhw + (- \\
& 2.08557e+12)*dhw**2 + (-0.0296774)*window_u**3 + (0.162963)*window_u**2*wall_r + \\
& (0.0420342)*window_u**2*roof_r + (-174.563)*window_u**2*infiltration + \\
& (0.0343954)*window_u**2*lights + (0.0773429)*window_u**2*equipment + (- \\
& 236586)*window_u**2*dhw + (0.0664858)*window_u*wall_r**2 + \\
& (0.00440975)*window_u*wall_r*roof_r + (2307.73)*window_u*wall_r*infiltration + \\
& (0.01448)*window_u*wall_r*lights + (-0.0441298)*window_u*wall_r*equipment + (- \\
& 11710.7)*window_u*wall_r*dhw + (-0.000642245)*window_u*roof_r**2 + (- \\
& 976.766)*window_u*roof_r*infiltration + (-0.0138646)*window_u*roof_r*lights + \\
& (0.0103039)*window_u*roof_r*equipment + (-173747)*window_u*roof_r*dhw + (- \\
& 2.32896e+07)*window_u*infiltration**2 + (470.107)*window_u*infiltration*lights + \\
& (1175.44)*window_u*infiltration*equipment + (4.11365e+08)*window_u*infiltration*dhw + \\
& (0.0135446)*window_u*lights**2 + (-0.0181657)*window_u*lights*equipment + \\
& (55917.9)*window_u*lights*dhw + (-0.0109939)*window_u*equipment**2 + (- \\
& 24945.8)*window_u*equipment*dhw + (-1.6294e+09)*window_u*dhw**2 + (- \\
& 0.396644)*wall_r**3 + (0.0143336)*wall_r**2*roof_r + (755.387)*wall_r**2*infiltration \\
& + (-0.00593676)*wall_r**2*lights + (-0.0435647)*wall_r**2*equipment + \\
& (113870)*wall_r**2*dhw + (-0.0023701)*wall_r*roof_r**2 + (- \\
& 180.196)*wall_r*roof_r*infiltration + (-0.00589051)*wall_r*roof_r*lights + \\
& (0.00866876)*wall_r*roof_r*equipment + (-29904.9)*wall_r*roof_r*dhw + \\
& (9.48112e+06)*wall_r*infiltration**2 + (-536.082)*wall_r*infiltration*lights + (- \\
& 561.395)*wall_r*infiltration*equipment + (6.42204e+08)*wall_r*infiltration*dhw + (- \\
& 0.0101928)*wall_r*lights**2 + (-0.00269524)*wall_r*lights*equipment + (- \\
& 5669.42)*wall_r*lights*dhw + (0.00562238)*wall_r*equipment**2 + (- \\
& 7730.49)*wall_r*equipment*dhw + (1.16812e+11)*wall_r*dhw**2 + (-0.133918)*roof_r**3 + \\
& (-172.864)*roof_r**2*infiltration + (-0.00360215)*roof_r**2*lights + (- \\
& 0.0086738)*roof_r**2*equipment + (-6332.56)*roof_r**2*dhw + (- \\
& 307659)*roof_r*infiltration**2 + (72.195)*roof_r*infiltration*lights + (- \\
& 81.1435)*roof_r*infiltration*equipment + (-1.78946e+08)*roof_r*infiltration*dhw + \\
& (0.00772068)*roof_r*lights**2 + (0.00163041)*roof_r*lights*equipment + (- \\
& 14927.9)*roof_r*lights*dhw + (0.00370104)*roof_r*equipment**2 + \\
& (21217.2)*roof_r*equipment*dhw + (2.26622e+10)*roof_r*dhw**2 + (- \\
& 4.97612e+10)*infiltration**3 + (6.81231e+06)*infiltration**2*lights + \\
& (5.98356e+06)*infiltration**2*equipment + (-6.87327e+12)*infiltration**2*dhw + (- \\
& 79.3981)*infiltration*lights**2 + (-195.889)*infiltration*lights*equipment + (- \\
& 2.56419e+08)*infiltration*lights*dhw + (-241.314)*infiltration*equipment**2 + (- \\
& 4.50749e+08)*infiltration*equipment*dhw + (-1.51409e+15)*infiltration*dhw**2 + (- \\
& 0.00215068)*lights**3 + (0.00120491)*lights**2*equipment + (-6903.47)*lights**2*dhw + \\
& (0.00329735)*lights*equipment**2 + (-15703.1)*lights*equipment*dhw + (- \\
& 7.38768e+09)*lights*dhw**2 + (0.00153238)*equipment**3 + (-3555.99)*equipment**2*dhw \\
& + (-2.98055e+10)*equipment*dhw**2 + (1.96195e+17)*dhw**3
\end{aligned}$$

### C.1.9 Fourth-Degree Polynomial Equation for HVAC C

$$\begin{aligned}
EUI = & 272.884 + (-9.1328)*window_u + (-25.388)*wall_r + (-23.5717)*roof_r + \\
& (165365)*infiltration + (-1.50517)*lights + (13.0953)*equipment + (4.59665e+07)*dhw + \\
& (3.77371)*window_u**2 + (-2.53458)*window_u*wall_r + (1.03783)*window_u*roof_r + \\
& (27270.4)*window_u*infiltration + (2.29243)*window_u*lights + \\
& (0.93989)*window_u*equipment + (5.91048e+06)*window_u*dhw + (7.98501)*wall_r**2 + (- \\
& 0.715638)*wall_r*roof_r + (-24636.7)*wall_r*infiltration + (0.102674)*wall_r*lights + \\
& (0.615373)*wall_r*equipment + (-4.17875e+06)*wall_r*dhw + (5.00223)*roof_r**2 + \\
& (7456.95)*roof_r*infiltration + (-0.850489)*roof_r*lights + (- \\
& 0.274927)*roof_r*equipment + (-2.1748e+06)*roof_r*dhw + (- \\
& 9.90677e+07)*infiltration**2 + (7967.6)*infiltration*lights + \\
& (7643.89)*infiltration*equipment + (3.19191e+10)*infiltration*dhw +
\end{aligned}$$

(0.352511)\*lights\*\*2 + (-0.249589)\*lights\*equipment + (421253)\*lights\*dhw +  
 (0.109992)\*equipment\*\*2 + (503986)\*equipment\*dhw + (-1.53415e+12)\*dhw\*\*2 + (-  
 0.0294581)\*window\_u\*\*3 + (1.08477)\*window\_u\*\*2\*wall\_r + (0.10082)\*window\_u\*\*2\*roof\_r  
 + (-11355.3)\*window\_u\*\*2\*infiltration + (-0.319172)\*window\_u\*\*2\*lights + (-  
 0.222498)\*window\_u\*\*2\*equipment + (-396449)\*window\_u\*\*2\*dhw +  
 (1.03365)\*window\_u\*wall\_r\*\*2 + (-0.285348)\*window\_u\*wall\_r\*roof\_r +  
 (555.412)\*window\_u\*wall\_r\*infiltration + (0.05383)\*window\_u\*wall\_r\*lights + (-  
 0.247867)\*window\_u\*wall\_r\*equipment + (-963293)\*window\_u\*wall\_r\*dhw + (-  
 0.00129579)\*window\_u\*roof\_r\*\*2 + (1681.75)\*window\_u\*roof\_r\*infiltration +  
 (0.0768787)\*window\_u\*roof\_r\*lights + (-0.0797404)\*window\_u\*roof\_r\*equipment + (-  
 168851)\*window\_u\*roof\_r\*dhw + (-3.47386e+07)\*window\_u\*infiltration\*\*2 + (-  
 881.659)\*window\_u\*infiltration\*lights + (3726.44)\*window\_u\*infiltration\*equipment +  
 (-4.52078e+09)\*window\_u\*infiltration\*dhw + (-0.00818644)\*window\_u\*lights\*\*2 + (-  
 0.0690497)\*window\_u\*lights\*equipment + (-728539)\*window\_u\*lights\*dhw + (-  
 0.0391073)\*window\_u\*equipment\*\*2 + (-339265)\*window\_u\*equipment\*dhw +  
 (5.15455e+11)\*window\_u\*dhw\*\*2 + (-1.66885)\*wall\_r\*\*3 + (0.162566)\*wall\_r\*\*2\*roof\_r +  
 (5790.12)\*wall\_r\*\*2\*infiltration + (0.109118)\*wall\_r\*\*2\*lights + (-  
 0.130733)\*wall\_r\*\*2\*equipment + (1.17481e+06)\*wall\_r\*\*2\*dhw +  
 (0.0297167)\*wall\_r\*roof\_r\*\*2 + (366.441)\*wall\_r\*roof\_r\*infiltration +  
 (0.0678819)\*wall\_r\*roof\_r\*lights + (-0.0245175)\*wall\_r\*roof\_r\*equipment +  
 (94371.5)\*wall\_r\*roof\_r\*dhw + (4.55677e+07)\*wall\_r\*infiltration\*\*2 + (-  
 671.393)\*wall\_r\*infiltration\*lights + (-2250.42)\*wall\_r\*infiltration\*equipment + (-  
 3.22873e+09)\*wall\_r\*infiltration\*dhw + (-0.0631033)\*wall\_r\*lights\*\*2 + (-  
 0.0496033)\*wall\_r\*lights\*equipment + (1583.23)\*wall\_r\*lights\*dhw +  
 (0.0550777)\*wall\_r\*equipment\*\*2 + (209250)\*wall\_r\*equipment\*dhw + (-  
 2.57189e+10)\*wall\_r\*dhw\*\*2 + (-0.591039)\*roof\_r\*\*3 + (-  
 1361.52)\*roof\_r\*\*2\*infiltration + (0.0967248)\*roof\_r\*\*2\*lights +  
 (0.0598751)\*roof\_r\*\*2\*equipment + (473273)\*roof\_r\*\*2\*dhw +  
 (2.65714e+07)\*roof\_r\*infiltration\*\*2 + (129.458)\*roof\_r\*infiltration\*lights + (-  
 636.012)\*roof\_r\*infiltration\*equipment + (-2.91274e+09)\*roof\_r\*infiltration\*dhw +  
 (0.0406732)\*roof\_r\*lights\*\*2 + (-0.00602798)\*roof\_r\*lights\*equipment + (-  
 77870.5)\*roof\_r\*lights\*dhw + (0.0203887)\*roof\_r\*equipment\*\*2 +  
 (6785.56)\*roof\_r\*equipment\*dhw + (2.40584e+11)\*roof\_r\*dhw\*\*2 + (-  
 1.29679e+11)\*infiltration\*\*3 + (-6.27636e+06)\*infiltration\*\*2\*lights +  
 (1.46862e+07)\*infiltration\*\*2\*equipment + (-7.3939e+12)\*infiltration\*\*2\*dhw + (-  
 201.921)\*infiltration\*lights\*\*2 + (340.086)\*infiltration\*lights\*equipment + (-  
 1.42275e+09)\*infiltration\*lights\*dhw + (-940.745)\*infiltration\*equipment\*\*2 + (-  
 2.3194e+09)\*infiltration\*equipment\*dhw + (7.47195e+14)\*infiltration\*dhw\*\*2 + (-  
 0.0286126)\*lights\*\*3 + (-0.00156693)\*lights\*\*2\*equipment + (36720.4)\*lights\*\*2\*dhw +  
 (0.0195096)\*lights\*equipment\*\*2 + (98345.8)\*lights\*equipment\*dhw +  
 (4.38642e+10)\*lights\*dhw\*\*2 + (0.0026374)\*equipment\*\*3 + (9822.63)\*equipment\*\*2\*dhw +  
 (-1.06689e+11)\*equipment\*dhw\*\*2 + (-4.58967e+17)\*dhw\*\*3 + (-0.104754)\*window\_u\*\*4 +  
 (-0.0176166)\*window\_u\*\*3\*wall\_r + (-0.0545091)\*window\_u\*\*3\*roof\_r +  
 (1009.86)\*window\_u\*\*3\*infiltration + (0.0540852)\*window\_u\*\*3\*lights +  
 (0.0398997)\*window\_u\*\*3\*equipment + (-4349.08)\*window\_u\*\*3\*dhw + (-  
 0.117871)\*window\_u\*\*2\*wall\_r\*\*2 + (0.00830865)\*window\_u\*\*2\*wall\_r\*roof\_r +  
 (13.9599)\*window\_u\*\*2\*wall\_r\*infiltration + (0.00667089)\*window\_u\*\*2\*wall\_r\*lights +  
 (0.0241087)\*window\_u\*\*2\*wall\_r\*equipment + (-95776)\*window\_u\*\*2\*wall\_r\*dhw + (-  
 0.0134524)\*window\_u\*\*2\*roof\_r\*\*2 + (-579.136)\*window\_u\*\*2\*roof\_r\*infiltration +  
 (0.0209609)\*window\_u\*\*2\*roof\_r\*lights + (-0.00687176)\*window\_u\*\*2\*roof\_r\*equipment +  
 (117741)\*window\_u\*\*2\*roof\_r\*dhw + (1.66692e+07)\*window\_u\*\*2\*infiltration\*\*2 + (-  
 379.697)\*window\_u\*\*2\*infiltration\*lights + (-  
 400.239)\*window\_u\*\*2\*infiltration\*equipment +  
 (2.99238e+08)\*window\_u\*\*2\*infiltration\*dhw + (0.00721827)\*window\_u\*\*2\*lights\*\*2 +  
 (0.00172317)\*window\_u\*\*2\*lights\*equipment + (-35254.7)\*window\_u\*\*2\*lights\*dhw + (-

0.000582358)\*window\_u\*\*2\*equipment\*\*2 + (44681.2)\*window\_u\*\*2\*equipment\*dhw + (-  
 6.02659e+10)\*window\_u\*\*2\*dhw\*\*2 + (-0.00518144)\*window\_u\*wall\_r\*\*3 + (-  
 0.00886254)\*window\_u\*wall\_r\*\*2\*roof\_r + (-590.229)\*window\_u\*wall\_r\*\*2\*infiltration +  
 (-0.00547616)\*window\_u\*wall\_r\*\*2\*lights + (0.00717756)\*window\_u\*wall\_r\*\*2\*equipment +  
 (-46803.3)\*window\_u\*wall\_r\*\*2\*dhw + (0.0125335)\*window\_u\*wall\_r\*roof\_r\*\*2 +  
 (16.3506)\*window\_u\*wall\_r\*roof\_r\*infiltration + (-  
 0.00162267)\*window\_u\*wall\_r\*roof\_r\*lights +  
 (0.00538222)\*window\_u\*wall\_r\*roof\_r\*equipment + (22193.2)\*window\_u\*wall\_r\*roof\_r\*dhw  
 + (-90683.2)\*window\_u\*wall\_r\*infiltration\*\*2 + (-  
 90.0485)\*window\_u\*wall\_r\*infiltration\*lights +  
 (131.056)\*window\_u\*wall\_r\*infiltration\*equipment +  
 (9.81879e+08)\*window\_u\*wall\_r\*infiltration\*dhw + (-  
 0.00824195)\*window\_u\*wall\_r\*lights\*\*2 + (-  
 0.000648912)\*window\_u\*wall\_r\*lights\*equipment + (29327.8)\*window\_u\*wall\_r\*lights\*dhw  
 + (-0.00332255)\*window\_u\*wall\_r\*equipment\*\*2 + (12313)\*window\_u\*wall\_r\*equipment\*dhw  
 + (1.00002e+11)\*window\_u\*wall\_r\*dhw\*\*2 + (-0.0034661)\*window\_u\*roof\_r\*\*3 +  
 (188.826)\*window\_u\*roof\_r\*\*2\*infiltration + (0.000849809)\*window\_u\*roof\_r\*\*2\*lights +  
 (-0.000475098)\*window\_u\*roof\_r\*\*2\*equipment + (-1511.22)\*window\_u\*roof\_r\*\*2\*dhw + (-  
 4.27772e+06)\*window\_u\*roof\_r\*infiltration\*\*2 + (-  
 31.2534)\*window\_u\*roof\_r\*infiltration\*lights +  
 (80.2819)\*window\_u\*roof\_r\*infiltration\*equipment +  
 (1.81326e+08)\*window\_u\*roof\_r\*infiltration\*dhw + (-  
 0.0017981)\*window\_u\*roof\_r\*lights\*\*2 + (0.000590347)\*window\_u\*roof\_r\*lights\*equipment  
 + (-31950.8)\*window\_u\*roof\_r\*lights\*dhw + (0.000727862)\*window\_u\*roof\_r\*equipment\*\*2  
 + (9044.06)\*window\_u\*roof\_r\*equipment\*dhw + (-4.61341e+10)\*window\_u\*roof\_r\*dhw\*\*2 +  
 (1.20108e+10)\*window\_u\*infiltration\*\*3 +  
 (1.73084e+06)\*window\_u\*infiltration\*\*2\*lights + (-  
 3.27286e+06)\*window\_u\*infiltration\*\*2\*equipment + (-  
 1.80698e+12)\*window\_u\*infiltration\*\*2\*dhw + (38.0208)\*window\_u\*infiltration\*lights\*\*2  
 + (14.4874)\*window\_u\*infiltration\*lights\*equipment +  
 (2.3413e+08)\*window\_u\*infiltration\*lights\*dhw +  
 (29.1662)\*window\_u\*infiltration\*equipment\*\*2 + (-  
 8.22526e+06)\*window\_u\*infiltration\*equipment\*dhw + (-  
 5.56441e+13)\*window\_u\*infiltration\*dhw\*\*2 + (0.00273653)\*window\_u\*lights\*\*3 + (-  
 0.00170203)\*window\_u\*lights\*\*2\*equipment + (-6626.44)\*window\_u\*lights\*\*2\*dhw +  
 (0.000469089)\*window\_u\*lights\*equipment\*\*2 + (15020.5)\*window\_u\*lights\*equipment\*dhw  
 + (9.22727e+10)\*window\_u\*lights\*dhw\*\*2 + (0.000703358)\*window\_u\*equipment\*\*3 +  
 (625.288)\*window\_u\*equipment\*\*2\*dhw + (-5.78634e+09)\*window\_u\*equipment\*dhw\*\*2 + (-  
 5.0919e+16)\*window\_u\*dhw\*\*3 + (0.0982775)\*wall\_r\*\*4 + (-0.00687603)\*wall\_r\*\*3\*roof\_r  
 + (-349.502)\*wall\_r\*\*3\*infiltration + (-0.00109202)\*wall\_r\*\*3\*lights +  
 (0.00500928)\*wall\_r\*\*3\*equipment + (-27573.6)\*wall\_r\*\*3\*dhw + (-  
 0.00394851)\*wall\_r\*\*2\*roof\_r\*\*2 + (10.6308)\*wall\_r\*\*2\*roof\_r\*infiltration + (-  
 0.00568715)\*wall\_r\*\*2\*roof\_r\*lights + (0.00388653)\*wall\_r\*\*2\*roof\_r\*equipment + (-  
 7753.09)\*wall\_r\*\*2\*roof\_r\*dhw + (-530883)\*wall\_r\*\*2\*infiltration\*\*2 + (-  
 40.1409)\*wall\_r\*\*2\*infiltration\*lights + (25.2814)\*wall\_r\*\*2\*infiltration\*equipment +  
 (1.00991e+08)\*wall\_r\*\*2\*infiltration\*dhw + (0.0014461)\*wall\_r\*\*2\*lights\*\*2 + (-  
 0.00143815)\*wall\_r\*\*2\*lights\*equipment + (-6904.15)\*wall\_r\*\*2\*lights\*dhw + (-  
 0.0020895)\*wall\_r\*\*2\*equipment\*\*2 + (9595.11)\*wall\_r\*\*2\*equipment\*dhw + (-  
 9.0562e+10)\*wall\_r\*\*2\*dhw\*\*2 + (-0.00241335)\*wall\_r\*roof\_r\*\*3 +  
 (87.9069)\*wall\_r\*roof\_r\*\*2\*infiltration + (-0.00167965)\*wall\_r\*roof\_r\*\*2\*lights + (-  
 0.00251461)\*wall\_r\*roof\_r\*\*2\*equipment + (5167.93)\*wall\_r\*roof\_r\*\*2\*dhw + (-  
 1.94339e+06)\*wall\_r\*roof\_r\*infiltration\*\*2 + (-  
 45.6955)\*wall\_r\*roof\_r\*infiltration\*lights +  
 (23.8715)\*wall\_r\*roof\_r\*infiltration\*equipment + (-  
 4.0324e+07)\*wall\_r\*roof\_r\*infiltration\*dhw + (0.00247367)\*wall\_r\*roof\_r\*lights\*\*2 +

(0.00127348)\*wall\_r\*roof\_r\*lights\*equipment + (-7178.98)\*wall\_r\*roof\_r\*lights\*dhw +  
 (0.000586308)\*wall\_r\*roof\_r\*equipment\*\*2 + (-1936.15)\*wall\_r\*roof\_r\*equipment\*dhw +  
 (-8.60789e+09)\*wall\_r\*roof\_r\*dhw\*\*2 + (-2.72517e+10)\*wall\_r\*infiltration\*\*3 +  
 (1.09825e+06)\*wall\_r\*infiltration\*\*2\*lights +  
 (2.17019e+06)\*wall\_r\*infiltration\*\*2\*equipment + (-  
 4.9785e+12)\*wall\_r\*infiltration\*\*2\*dhw + (35.9302)\*wall\_r\*infiltration\*lights\*\*2 + (-  
 6.93952)\*wall\_r\*infiltration\*lights\*equipment +  
 (2.27313e+07)\*wall\_r\*infiltration\*lights\*dhw + (-  
 0.809576)\*wall\_r\*infiltration\*equipment\*\*2 + (-  
 9.25947e+07)\*wall\_r\*infiltration\*equipment\*dhw +  
 (6.55176e+14)\*wall\_r\*infiltration\*dhw\*\*2 + (0.000217727)\*wall\_r\*lights\*\*3 +  
 (0.0013019)\*wall\_r\*lights\*\*2\*equipment + (3617.67)\*wall\_r\*lights\*\*2\*dhw +  
 (0.000853727)\*wall\_r\*lights\*equipment\*\*2 + (5325.81)\*wall\_r\*lights\*equipment\*dhw + (-  
 6.02156e+09)\*wall\_r\*lights\*dhw\*\*2 + (-0.000470147)\*wall\_r\*equipment\*\*3 + (-  
 4328.02)\*wall\_r\*equipment\*\*2\*dhw + (-2.12606e+10)\*wall\_r\*equipment\*dhw\*\*2 +  
 (4.39549e+16)\*wall\_r\*dhw\*\*3 + (0.02461)\*roof\_r\*\*4 + (1.27103)\*roof\_r\*\*3\*infiltration  
 + (-0.00338852)\*roof\_r\*\*3\*lights + (-0.000472439)\*roof\_r\*\*3\*equipment + (-  
 14048.1)\*roof\_r\*\*3\*dhw + (-1.11996e+06)\*roof\_r\*\*2\*infiltration\*\*2 +  
 (38.0953)\*roof\_r\*\*2\*infiltration\*lights + (4.7747)\*roof\_r\*\*2\*infiltration\*equipment +  
 (2.70277e+08)\*roof\_r\*\*2\*infiltration\*dhw + (-0.00234417)\*roof\_r\*\*2\*lights\*\*2 + (-  
 0.000160102)\*roof\_r\*\*2\*lights\*equipment + (-3733.1)\*roof\_r\*\*2\*lights\*dhw + (-  
 0.000887691)\*roof\_r\*\*2\*equipment\*\*2 + (-7473)\*roof\_r\*\*2\*equipment\*dhw + (-  
 3.01814e+10)\*roof\_r\*\*2\*dhw\*\*2 + (-1.31465e+10)\*roof\_r\*infiltration\*\*3 + (-  
 242232)\*roof\_r\*infiltration\*\*2\*lights + (474073)\*roof\_r\*infiltration\*\*2\*equipment +  
 (3.52235e+12)\*roof\_r\*infiltration\*\*2\*dhw + (-28.1327)\*roof\_r\*infiltration\*lights\*\*2 +  
 (-5.01473)\*roof\_r\*infiltration\*lights\*equipment +  
 (9.29551e+07)\*roof\_r\*infiltration\*lights\*dhw + (-  
 11.4098)\*roof\_r\*infiltration\*equipment\*\*2 +  
 (2.85876e+07)\*roof\_r\*infiltration\*equipment\*dhw + (-  
 5.50569e+14)\*roof\_r\*infiltration\*dhw\*\*2 + (-0.00122936)\*roof\_r\*lights\*\*3 + (-  
 0.000632984)\*roof\_r\*lights\*\*2\*equipment + (7104.26)\*roof\_r\*lights\*\*2\*dhw +  
 (0.000583566)\*roof\_r\*lights\*equipment\*\*2 + (572.071)\*roof\_r\*lights\*equipment\*dhw +  
 (7.20867e+09)\*roof\_r\*lights\*dhw\*\*2 + (-0.000150378)\*roof\_r\*equipment\*\*3 + (-  
 1380.31)\*roof\_r\*equipment\*\*2\*dhw + (1.15098e+10)\*roof\_r\*equipment\*dhw\*\*2 +  
 (1.28758e+16)\*roof\_r\*dhw\*\*3 + (1.90341e+14)\*infiltration\*\*4 + (-  
 1.15748e+09)\*infiltration\*\*3\*lights + (-2.69166e+10)\*infiltration\*\*3\*equipment +  
 (6.78075e+16)\*infiltration\*\*3\*dhw + (-241901)\*infiltration\*\*2\*lights\*\*2 +  
 (640215)\*infiltration\*\*2\*lights\*equipment + (-5.44671e+11)\*infiltration\*\*2\*lights\*dhw  
 + (689705)\*infiltration\*\*2\*equipment\*\*2 + (-  
 4.40707e+11)\*infiltration\*\*2\*equipment\*dhw + (-7.35499e+18)\*infiltration\*\*2\*dhw\*\*2 +  
 (7.25666)\*infiltration\*lights\*\*3 + (-14.1133)\*infiltration\*lights\*\*2\*equipment +  
 (6.16145e+07)\*infiltration\*lights\*\*2\*dhw + (-  
 23.5611)\*infiltration\*lights\*equipment\*\*2 + (-  
 6.07551e+07)\*infiltration\*lights\*equipment\*dhw +  
 (4.25363e+13)\*infiltration\*lights\*dhw\*\*2 + (3.094)\*infiltration\*equipment\*\*3 +  
 (6.26004e+07)\*infiltration\*equipment\*\*2\*dhw +  
 (1.80371e+14)\*infiltration\*equipment\*dhw\*\*2 + (3.2951e+20)\*infiltration\*dhw\*\*3 +  
 (0.000885709)\*lights\*\*4 + (0.000143564)\*lights\*\*3\*equipment + (-  
 438.928)\*lights\*\*3\*dhw + (9.82188e-06)\*lights\*\*2\*equipment\*\*2 +  
 (1443.6)\*lights\*\*2\*equipment\*dhw + (-1.53423e+10)\*lights\*\*2\*dhw\*\*2 + (-  
 0.000380296)\*lights\*equipment\*\*3 + (-220.082)\*lights\*equipment\*\*2\*dhw + (-  
 1.77018e+10)\*lights\*equipment\*dhw\*\*2 + (1.38611e+16)\*lights\*dhw\*\*3 +  
 (0.000129958)\*equipment\*\*4 + (-1115.68)\*equipment\*\*3\*dhw +  
 (3.35844e+09)\*equipment\*\*2\*dhw\*\*2 + (7.73512e+15)\*equipment\*dhw\*\*3 +  
 (3.59185e+22)\*dhw\*\*4

## C.2 Surrogate Modelling Code

Included in this section is the Python code used for running the simulations, postprocessing the data and training the surrogate models.

### C.2.1 main.py

```
'''
This code was developed by Alexis Minniti with support from Dr. Costa Kapsis and Dr.
Harry Vallianos.
The purpose of this code is to generate building energy use data using EnergyPlus and
use that data to train surrogate models.
This code was developed in Python version 3.12
'''

# import standard libraries
import pathlib
import pandas as pd # ver 2.2.2

# import custom modules
import parameterize_functions
import postprocess_results
import surrogate_model

# Step 0: Create file paths & folder structure
ENERGY_PLUS_FOLDER = pathlib.Path("C:/EnergyPlusV24-1-0") # The path to the folder of
energy plus
IDF_PATH_A =
pathlib.Path(__file__).parent.joinpath("inputs/ASHRAE901_ApartmentMidRise_STD2004_Tor
onto_HVAC_A.idf") # The location of the idf file
IDF_PATH_B =
pathlib.Path(__file__).parent.joinpath("inputs/ASHRAE901_ApartmentMidRise_STD2004_Tor
onto_HVAC_B.idf") # The location of the idf file
IDF_PATH_C =
pathlib.Path(__file__).parent.joinpath("inputs/ASHRAE901_ApartmentMidRise_STD2004_Tor
onto_HVAC_C.idf") # The location of the idf file
EPW_PATH = pathlib.Path(__file__).parent.joinpath("inputs/CAN_ON_Bishop-
Toronto.City.AP.712650_TMYx.epw") # The location of the epw file
OUTPUT_PATH = pathlib.Path(__file__).parent.joinpath("output")
INPUTS_FILE = pathlib.Path(__file__).parent.joinpath("inputs/inputs.csv")
OUTPUT_PATH.mkdir(exist_ok=True) # Create the output folder. Don't throw an error if
it already exists
idf_output_path = OUTPUT_PATH.joinpath("idf_files")
idf_output_path.mkdir(exist_ok=True)
results_path = OUTPUT_PATH.joinpath("results")
results_path.mkdir(exist_ok=True)
models_path = OUTPUT_PATH.joinpath("surrogate_models")
models_path.mkdir(exist_ok=True)

# Step 1: Read the idf and the inputs
parameterize_functions.convert_idf_to_epjson(IDF_PATH_A, OUTPUT_PATH,
ENERGY_PLUS_FOLDER)
```

```

idf_a =
parameterize_functions.read_epjson(OUTPUT_PATH.joinpath(f"{IDF_PATH_A.stem}.epJSON"))
parameterize_functions.convert_idf_to_epjson(IDF_PATH_B, OUTPUT_PATH,
ENERGY_PLUS_FOLDER)
idf_b =
parameterize_functions.read_epjson(OUTPUT_PATH.joinpath(f"{IDF_PATH_B.stem}.epJSON"))
parameterize_functions.convert_idf_to_epjson(IDF_PATH_C, OUTPUT_PATH,
ENERGY_PLUS_FOLDER)
idf_c =
parameterize_functions.read_epjson(OUTPUT_PATH.joinpath(f"{IDF_PATH_C.stem}.epJSON"))
simulation_parameters = pd.read_csv(INPUTS_FILE, index_col='Label')
simulation_parameters['Field'] = simulation_parameters['Field'].str.replace(" |-",
"_", regex=True).str.lower() # The epJSON schema takes field names without any spaces
or dashes, but with underscores and all lowercase. So we need to modify the field
names to match the schema

# Step 2: Modify the idf with the inputs and save each idf in one folder with a
special name
modified_inputs =
parameterize_functions.create_latin_hypercube(simulation_parameters,2100,12345)
modified_inputs.to_csv(OUTPUT_PATH.joinpath("modified_inputs.csv")) # Save a csv with
all the inputs
for index, row in modified_inputs.iterrows():
    if (row["HVAC"] == 0):
        print("Generating idf file",index)
        modified_idf = parameterize_functions.modify_idf(idf_a,
simulation_parameters, row)
        parameterize_functions.save_idf(modified_idf, idf_output_path, row,
ENERGY_PLUS_FOLDER)
    if (row["HVAC"] == 1):
        print("Generating idf file",index)
        modified_idf = parameterize_functions.modify_idf(idf_b,
simulation_parameters, row)
        parameterize_functions.save_idf(modified_idf, idf_output_path, row,
ENERGY_PLUS_FOLDER)
    if (row["HVAC"] == 2):
        print("Generating idf file",index)
        modified_idf = parameterize_functions.modify_idf(idf_c,
simulation_parameters, row)
        parameterize_functions.save_idf(modified_idf, idf_output_path, row,
ENERGY_PLUS_FOLDER)

# Step 3: Run the simulations
for index, (idf_file) in enumerate(idf_output_path.iterdir()):
    print("Running idf file",index)
    parameterize_functions.run_simulation(idf_file, results_path, EPW_PATH,
ENERGY_PLUS_FOLDER)

# Step 4: Post-process the results
modified_inputs = pd.read_csv(OUTPUT_PATH.joinpath("modified_inputs.csv"),
index_col=0)
modified_inputs_postprocessed = postprocess_results.read_results(modified_inputs,
results_path, "sql")
modified_inputs_postprocessed.to_csv(OUTPUT_PATH.joinpath("postprocessed_data.csv"))

```

```
# Step 5: Train surrogate models using the simulation results
postprocessed_data = pd.read_csv(OUTPUT_PATH.joinpath("postprocessed_data.csv"))
surrogate_model.train_models(postprocessed_data, models_path)

# Step 6: Evaluate surrogate models
postprocessed_data = pd.read_csv(OUTPUT_PATH.joinpath("postprocessed_data.csv"))
surrogate_model.model_metrics(postprocessed_data, models_path)
```

## C.2.2 parameterize\_functions.py

```
'''
This code was developed by Alexis Minniti with support from Dr. Costa Kapsis and Dr.
Harry Vallianos.
The purpose of this code is to generate and run EnergyPlus files.
This code was developed in Python version 3.12
'''

# import standard libraries
from pathlib import Path
import pandas as pd # ver 2.2.2
import numpy as np # ver 2.1.0
from subprocess import run, DEVNULL
import json
from shutil import copy, rmtree
from natsort import natsorted # ver 8.4.0
from itertools import product
from copy import deepcopy
from scipy.stats import qmc # ver 1.15.1

def convert_idf_to_epjson(original_idf_location: Path, output_path: Path, eplus_path:
Path):
    """
    Convert idf to epjson and vice-versa. New version of EnergyPlus allow
    a --convert-only flag so that no simulation is run and no weather file is needed,
    but since we are dealing a lot with older versions, we will use the old method
    that requires the simulation to fully run.

    Args:
    original_idf_location (pathlib.Path): The location of the idf
    output_path (pathlib.Path): The output folder
    eplus_path (pathlib.Path): The folder of energyplus
    """
    # Create a new temporary folder for all EnergyPlus files
    temp_folder = output_path.joinpath("temp_folder")
    temp_folder.mkdir(exist_ok=True)
    # Create the EnergyPlus command to run
    eplus_exe = Path(eplus_path).joinpath("energyplus.exe")
    command = f"{eplus_exe} -d {temp_folder} -c"
    command = f"{command} {original_idf_location}"
    # We know that running energyplus without a weather file will throw an error,
    # but not before it converts the idf to epjson. That means that I can run it,
    # catch the exception and stop it there
    try:
        run(command, universal_newlines=True, check=True, stderr=DEVNULL,
        stdout=DEVNULL)
```

```

except Exception:
    pass
# Move the epJSON file to the output folder
if original_idf_location.suffix == '.idf':
    file_to_move =
temp_folder.joinpath(original_idf_location.name).with_suffix(".epJSON")
elif original_idf_location.suffix == '.epJSON':
    file_to_move =
temp_folder.joinpath(original_idf_location.name).with_suffix(".idf")
copy(file_to_move.as_posix(), output_path)
# Delete the temporary folder
rmtree(temp_folder)

def read_epjson(epjson_path: Path | str) -> dict:
    """
    Get the epjson of the E+ version from specified folder.

    Args:
    folder_path (pathlib.Path | str): The folder of the E+ version.

    Returns:
    dict: The epJSON
    """
    epjson_path = Path(epjson_path)
    with open(epjson_path, "r", encoding="utf-8") as file:
        epjson_schema = json.load(file)
    return epjson_schema

def update_idf(original_idf_location: Path, output_path: Path, eplus_path: Path,
old_version: str | None = None) -> dict:
    """
    Update the idf to the version of Energy+, convert it to epJSON and read it

    Args:
    original_idf_location (pathlib.Path): The original location of the idf
    output_path (pathlib.Path): The output folder
    eplus_path (pathlib.Path): The Energy+ folder
    old_version (str | None, optional): The version of the old idf. Defaults to None,
    in which case the script tries to convert the file to an epjson and read the
    version.

    Returns:
    dict: The epJSON
    """
    # Identify the folder that contains the IDF Version Updaters
    updater_folder = eplus_path.joinpath("PreProcess/IDFVersionUpdater")
    # Get the versions we can process
    versions = natsorted([file.stem[1:-8] for file in updater_folder.rglob("*.idd")])
    # If the version of the old file is not provided, try to convert the idf to
    epJSON and read
    # the version from there. Note that for very old version this will not work
    if not old_version:
        convert_idf_to_epjson(original_idf_location, output_path, eplus_path)
        epjson =
    read_epjson(output_path.joinpath(f"{original_idf_location.stem}.epJSON"))

```

```

        # Read the version of the file
        old_version = (
            f"{epjson['Version']['Version 1']['version_identifier'].replace('.', '-')
'')}-0"
        )
        # Read the version of Energy+
        new_version = eplus_path.stem.split("V")[1]
        # If the versions are the same return the epJSON
        if old_version == new_version:
            return
        output_idf_location = output_path.joinpath(original_idf_location.name)
        old_index = versions.index(old_version)
        new_index = versions.index(new_version)
        # Unfortunately we need to run the updater for every version
        for version_index in range(old_index, new_index):
            transition_exe = (
                f"Transition-V{versions[version_index]}-to"
                f"-V{versions[version_index+1]}.exe"
            )
            command = updater_folder.joinpath(transition_exe)
            copy(original_idf_location.as_posix(), output_idf_location)
            final_command = f"{command} {output_idf_location}"
            run(
                final_command, universal_newlines=True, cwd=updater_folder, check=True
            )
        # Delete the two files that are created in the process with extensions .idfnew
        # and .idfold
        output_path.joinpath(f"{original_idf_location.name}new").unlink()
        output_path.joinpath(f"{original_idf_location.name}old").unlink()

def create_full_factorial(inputs: pd.DataFrame) -> pd.DataFrame:
    """
    Create all possible combinations of the parameters in the inputs dataframe

    Args:
    inputs (pd.DataFrame): The dataframe that includes the desired inputs

    Returns:
    pd.DataFrame: A dataframe that includes all possible combinations
    """
    # First create a dictionary with all possible values for each parameter
    parameter_values = {}
    for row_name, row in inputs.iterrows():
        parameter_values[row_name] = np.linspace(row["Min_value"], row["Max_value"],
row["Number_samples"])
    # Then return a dataframe that include the cartesian product of these values. The
dataframe
    # has as many rows as combinations and as many columns as parameters
    full_factorial = pd.DataFrame(list(product(*parameter_values.values()))),
columns=parameter_values.keys())
    return full_factorial.round(5)

def create_latin_hypercube(inputs: pd.DataFrame, n:int, seed:int) -> pd.DataFrame:
    """
    Create latin hypercube of the parameters in the inputs dataframe

```

Args:  
 inputs (pd.DataFrame): The dataframe that includes the desired inputs  
 n (int): The number of samples to take from the LHS

Returns:  
 pd.DataFrame: A dataframe that includes latin hypercube  
 """

```
# set LHS dimension equal to number of rows in inputs.csv
d = inputs.shape[0]
# set lower bounds for scaling equal to Min_value column of inputs.csv
l_bounds = inputs.loc[:, "Min_value"]
# set upper bounds for scaling equal to Max_value column of inputs.csv
u_bounds = inputs.loc[:, "Max_value"]
# generate latin hypercube in dimension d, all values are between 0 and 1
latin_hypercube = (qmc.LatinHypercube(d, rng=np.random.default_rng(seed)))
# randomly get n samples from the latin hypercube
latin_hypercube = latin_hypercube.random(n)
# convert continuous to discrete values
for i, (row_name, row) in enumerate(inputs.iterrows()):
    if (row["Discrete"] != 0):
        latin_hypercube[:, i] =
np.floor(latin_hypercube[:, i]*row["Discrete"])/(row["Discrete"]-1)
# scale latin hypercube based on bounds
latin_hypercube = qmc.scale(latin_hypercube, l_bounds, u_bounds)
# transpose latin hypercube
latin_hypercube = np.transpose(latin_hypercube)
# create dictionary of latin hypercube parameter values
parameter_values = {}
for i, (row_name, row) in enumerate(inputs.iterrows()):
    parameter_values[row_name] = latin_hypercube[i]
# convert dictionary to dataframe
output = pd.DataFrame.from_dict(parameter_values)
return output.round(8)
```

```
def modify_idf(original_idf: dict, inputs: pd.DataFrame, combination: pd.Series) ->
dict:
    """
```

Modify the original idf with the inputs and the combination

Args:  
 original\_idf (dict): The original idf as a dictionary  
 inputs (pd.DataFrame): The inputs from the inputs file  
 combination (pd.Series): The combination of parameters we are modifying

Returns:  
 dict: The modified idf  
 """

```
# Make sure to deepcopy the original dictionary, otherwise the original will be
modified as well
modified_idf = deepcopy(original_idf)
# Iterate through inputs and modify idf entries
for parameter_label, parameter in inputs.iterrows():
    if (parameter_label != "HVAC"):
```

```

        if (parameter_label == "dhw"):
            dhw_object_names = modified_idf[parameter["Class"]].keys()
            for dhw_object_name in dhw_object_names:
                if (dhw_object_name[0] == "M"):

modified_idf[parameter["Class"]][dhw_object_name][parameter["Field"]] =
2*combination[parameter_label]
                else:

modified_idf[parameter["Class"]][dhw_object_name][parameter["Field"]] =
combination[parameter_label]
                elif (parameter['Class'] == "Schedule:Compact"):

modified_idf[parameter["Class"]][parameter["Object"]][parameter["Field"]][parameter["
Index"]-1]["field"] = combination[parameter_label]
                else:

modified_idf[parameter['Class']][parameter['Object']][parameter['Field']] =
combination[parameter_label]
            return modified_idf

def save_idf(modified_idf: dict, output_path: Path, combination: pd.Series,
eplus_path: Path, keep_epjson: bool = False) -> None:
    """
    Save the modified idf to a file

    Args:
    modified_idf (dict): The modified idf
    output_path (pathlib.Path): The output path
    combination (pd.Series): The combination of parameters we are modifying
    eplus_path (pathlib.Path): The folder of energyplus
    keep_epjson (bool, optional): Whether to keep the epJSON as well. Defaults to
False.
    """
    # Create the name of the idf
    idf_name = f"{'_'.join(combination.values.astype(str))}.epJSON"
    # Save the dict as a json file
    with open(output_path.joinpath(idf_name), "w", encoding="utf-8") as file:
        json.dump(modified_idf, file, indent=4)
    # Now transform it to an idf using Energyplus
    convert_idf_to_epjson(output_path.joinpath(idf_name), output_path, eplus_path)
    # If we don't want to keep the epJSON, delete it
    if not keep_epjson:
        output_path.joinpath(idf_name).unlink()

def run_simulation(idf_location: Path, output_path: Path, epw_path: Path, eplus_path:
Path):
    """
    Run the EnergyPlus simulation

    Args:
    idf_location (pathlib.Path): The location of the idf
    output_path (pathlib.Path): The output folder
    epw_path (pathlib.Path): The location of the weather file
    eplus_path (pathlib.Path): The folder of energyplus

```

```

"""
# Create the folder name for the energyplus results
output_folder = output_path.joinpath(f"{idf_location.stem}")
if output_folder.is_dir():
    print(f"The folder '{output_folder}' exists.")
else:
    eplus_exe = Path(eplus_path).joinpath("energyplus.exe")
    command = f"{eplus_exe} -d {output_folder} -w {epw_path}"
    command = f"{command} {idf_location}"
    run(command, universal_newlines=True, check=True)

```

### C.2.3 postprocess\_results.py

```

'''
This code was developed by Alexis Minniti with support from Dr. Costa Kapsis and Dr.
Harry Vallianos.
The purpose of this code is to extract specified data from EnergyPlus result files.
This code was developed in Python version 3.12
'''

```

```

# import standard libraries
from pathlib import Path
import pandas as pd # ver 2.2.2
import sqlite3

```

```

def read_results(modified_inputs: pd.DataFrame, results_folder_path: str | Path,
from_source: str = "sql") -> pd.DataFrame:
    """

```

Read results

Args:

modified\_inputs (dataframe): Dataframe containing map of what results to look for  
results\_folder\_path (str | Path): Path pointing to folder where results are  
stored

from\_source (str): String indicating which file type the data is stored in (sql  
or csv)

Returns:

energy\_results (dataframe): Dataframe containing KPIs

"""

```

results_folder_path = Path(results_folder_path)
energy_results = []
# Iterate over the rows of the dataframe
for _, row in modified_inputs.iterrows():
    print("Processing results file",_)
    # Define the name of the folder that you should look into
    idf_name = f"'_{row.values.astype(str)}'"
    # Fetch the KPI you want and append it to the list
    if from_source == "csv":
        energy_result = read_csv_result(
            results_folder_path.joinpath(f"{idf_name}/eplustbl.csv")
        )
    elif from_source == "sql":
        energy_result = read_sql_result(

```

```

        results_folder_path.joinpath(f"{idf_name}/eplusout.sql")
    )
    for variable, value in row.items():
        energy_result[variable] = value
    energy_results.append(energy_result)
    return pd.concat(energy_results)

def read_csv_result(csv_file_path: str | Path) -> float:
    """
    Read results from the csv file

    Args:
    csv_file_path (str|Path): The path to the csv file

    Returns:
    results (dataframe): Dataframe containing KPI
    """
    csv_file_path = Path(csv_file_path)
    # The csv file is not very well formatted. Therefore, we can only read uniform
    parts of it that look
    # like "tables". For example in this case we skip the first 13 rows and only read
    the table with
    # the summary that also appears in the html file
    data = pd.read_csv(
        csv_file_path, skiprows=13, nrows=4, usecols=[1, 2, 3, 4], index_col=0
    )
    # Only return the total energy per conditioned area
    return data

def read_sql_result(sql_file_path: str | Path) -> float:
    """
    Read results from the sql file

    Args:
    sql_file_path (str|Path): The path to the sql file

    Returns:
    results (dataframe): Dataframe containing KPI
    """
    sql_file_path = Path(sql_file_path)
    # Create a URI
    sql_uri = "{}?mode=ro".format(sql_file_path.as_uri())

    # Define your query. This defined which data exactly you want to extract from the
    sql file
    # The following query fetches all table names. Try running the following query
    and printing it
    query = "SELECT * FROM TabularDataWithStrings"

    # Establish the connection to the sql, run the query and save the results in a
    pandas dataframe
    with sqlite3.connect(sql_uri, uri=True) as connection:
        table = pd.read_sql(query, connection)

```

```

# Calculate or fetch the metric you want
eui = table.loc[
    (table.ReportName == "AnnualBuildingUtilityPerformanceSummary")
    & (table.TableName == "Site and Source Energy")
    & (table.ColumnName == "Energy Per Total Building Area")
    & (table.RowName == "Total Site Energy"),
    ["Value", "ReportName", "TableName", "RowName", "ColumnName", "Units"],
]
results = pd.concat([eui])
return results

```

## C.2.4 surrogate\_model.py

```

'''
This code was developed by Alexis Minniti with support from Dr. Costa Kapsis and Dr.
Harry Vallianos.
The purpose of this code is to train and evaluate surrogate models.
This code was developed in Python version 3.12
'''

# import standard libraries
from pathlib import Path
import pandas as pd # ver 2.2.2
import joblib # ver 1.4.2
import numpy as np # ver 2.1.0
import matplotlib.pyplot as plt # ver 3.10.1
import sympy as sp # ver 1.14.0
from sklearn.model_selection import train_test_split, GridSearchCV,
LearningCurveDisplay, ValidationCurveDisplay, validation_curve # ver 1.6.1
from sklearn.pipeline import Pipeline
from sklearn.compose import ColumnTransformer
from sklearn.preprocessing import StandardScaler, OneHotEncoder, PolynomialFeatures
from sklearn.linear_model import LinearRegression, Ridge
from sklearn.neural_network import MLPRegressor
from sklearn.metrics import r2_score, mean_absolute_error, root_mean_squared_error,
make_scorer

def mean_bias_error(y_true, y_pred):
    """
    Calculates the Mean Bias Error (MBE) between true and predicted values

    Args:
        y_true (array-like): Array of observed (true) values
        y_pred (array-like): Array of predicted values

    Returns:
        float: The Mean Bias Error
    """
    y_true = np.asarray(y_true, dtype=float)
    y_pred = np.asarray(y_pred, dtype=float)
    return np.mean(y_pred - y_true)

def normalized_mean_bias_error(y_true, y_pred):
    """

```

Calculates the Normalized Mean Bias Error (NMBE) between true and predicted values

```
Args:
    y_true (array-like): Array of observed (true) values
    y_pred (array-like): Array of predicted values

Returns:
    float: The Normalized Mean Bias Error
"""
y_true = np.asarray(y_true, dtype=float)
y_pred = np.asarray(y_pred, dtype=float)
try:
    return np.mean(y_pred - y_true) / np.mean(y_true) * 100
except ZeroDivisionError:
    return "Cannot divide by zero"
```

```
def normalized_root_mean_squared_error(y_true, y_pred):
    """
    Calculates the Root Mean Squared Error (RMSE) between true and predicted values
```

```
Args:
    y_true (array-like): Array of observed (true) values.
    y_pred (array-like): Array of predicted values.

Returns:
    float: The Root Mean Squared Error.
"""
y_true = np.asarray(y_true, dtype=float)
y_pred = np.asarray(y_pred, dtype=float)
try:
    return np.sqrt(np.mean((np.array(y_true) - np.array(y_pred))**2)) /
np.mean(y_true) * 100
except ZeroDivisionError:
    return "Cannot divide by zero"
```

```
def recover_model_equation(pipeline, feature_names):
    """
    Extracts the regression equation from a scikit-learn pipeline that includes
    PolynomialFeatures, StandardScaler, and a linear model (e.g., Ridge).
    The function undoes the effect of standard scaling and builds the equation
    in the original input feature scale.
```

```
Args:
    pipeline (Pipeline): A fitted scikit-learn Pipeline containing
        'poly' (PolynomialFeatures),
        'scaler' (StandardScaler), and
        'ridge' or 'linearregression' as steps.
    feature_names (list of str): List of original feature names.
```

```
Returns:
    equation (str): Equation in original input feature scale with named
variables.
```

```
"""
```

```

# Extract pipeline steps
poly = pipeline.named_steps['poly']
scaler = pipeline.named_steps['scaler']
model = pipeline.named_steps['ridge'] # or 'linearregression'
# Get input feature names
poly_feature_names = poly.get_feature_names_out(feature_names)
# Transform coefficients back to original scale
means = scaler.mean_
scales = scaler.scale_
coefs = model.coef_
intercept = model.intercept_
unscaled_coefs = coefs / scales
unscaled_intercept = intercept - np.sum((means / scales) * coefs)
# Build equation string
equation = f'{unscaled_intercept:.6g}'
for name, coef in zip(poly_feature_names, unscaled_coefs):
    name = name.replace(" ", "") # replace implicit multiplication of adjacent
terms with * operator
    name = name.replace("^", "**") # replace ^ with **
    equation += f' + ({coef:.6g})*{name}'
return f"{equation}"

def train_models(postprocessed_data: pd.DataFrame, results_folder_path: str | Path):
    """
    Trains polynomial and MLP surrogate models

    Args:
        postprocessed_data (dataframe): Dataframe containing training data
        results_folder_path (str | Path): Path pointing to where training data is
located
    """
    # define list of scoring metrics to use in grid search
    scoring = {
        'r2': make_scorer(r2_score, greater_is_better=True),
        'mbe': make_scorer(mean_bias_error, greater_is_better=False),
        'mae': make_scorer(mean_absolute_error, greater_is_better=False),
        'rmse': make_scorer(root_mean_squared_error, greater_is_better=False),
        'nmbe': make_scorer(normalized_mean_bias_error, greater_is_better=False),
        'nrmse': make_scorer(normalized_root_mean_squared_error,
greater_is_better=False)
    }
    # train separate models for each HVAC model (A, B, C)
    char_list = ['A', 'B', 'C']
    for i in range (0,3):
        # get training data
        selected_data = postprocessed_data.loc[(postprocessed_data['ColumnName'] ==
'Energy Per Total Building Area') & (postprocessed_data['HVAC'] == i)]
        X = selected_data[['window_u', 'wall_r', 'roof_r', 'infiltration', 'lights',
'equipment', 'dhw']]
        y = np.ravel(selected_data[['Value']]).to_numpy()
        # split training and testing data sets
        X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.1,
random_state=0)
        #'''
        # polynomial model training

```

```

# create pipeline
pipeline = Pipeline([
    ('poly', PolynomialFeatures(include_bias=False)),
    ('scaler', StandardScaler()),
    ('ridge', Ridge())
])
# grid search parameters
param_grid = {
    'poly__degree': [1,2,3,4,5], # polynomial degrees
    'ridge__alpha': [0.001, 0.01, 0.1, 1.0] # L2 regularization
}
# grid search setup
grid = GridSearchCV(pipeline, param_grid, refit = 'r2', verbose = 3,
n_jobs=1, cv = 10, return_train_score=True, scoring=scoring)
# fit model
grid.fit(X_train, y_train)
# persist pipeline
target_file = results_folder_path/f"model_poly_HVAC_{char_list[i]}.pkl"
joblib.dump(grid, target_file)
#'''
# mlp
# create pipeline
pipeline = Pipeline([
    ('scaler', StandardScaler()),
    ('model', MLPRegressor(learning_rate='adaptive', early_stopping=True,
validation_fraction=0.1, n_iter_no_change=10, max_iter=500, solver='lbfgs',
activation='relu'))
])
# grid search parameters
param_grid = {
    'model__hidden_layer_sizes': [(50, 50), (100, 50), (100, 100)], # Small
to moderately deep networks
    'model__activation': ['relu', 'tanh'], # 'logistic' can be slow and less
effective for regression
    'model__solver': ['adam', 'lbfgs'], # 'lbfgs' is good for small
datasets; 'adam' works well generally
    'model__alpha': [1e-5, 1e-4, 1e-3, 1e-2], # L2 regularization
}
# grid search setup
grid = GridSearchCV(pipeline, param_grid, refit = 'r2', verbose = 3,
n_jobs=1, cv = 10, return_train_score=True, scoring=scoring)
# fit model
grid.fit(X_train, y_train)
# persist pipeline
target_file = results_folder_path/f"model_mlp_HVAC_{char_list[i]}.pkl"
joblib.dump(grid, target_file)
#'''

def model_metrics(postprocessed_data: pd.DataFrame, results_folder_path: str | Path):
    """
    Evaluates polynomial and MLP surrogate models

    Args:
        postprocessed_data (dataframe): Dataframe containing training data

```

```

        results_folder_path (str | Path):Path pointing to where training data is
located
    """
    # train models for each HVAC model (A, B, C)
    char_list = ['A', 'B', 'C']
    for i in range (0,3):
        # get data
        selected_data = postprocessed_data.loc[(postprocessed_data['ColumnName'] ==
'Energy Per Total Building Area') & (postprocessed_data['HVAC'] == i)]
        X = selected_data[['window_u', 'wall_r', 'roof_r', 'infiltration', 'lights',
'equipment', 'dhw']]
        y = np.ravel(selected_data[['Value']]).to_numpy())
        # split training and testing data sets
        X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.1,
random_state=0)
        #'''
        # polynomial
        # load model
        target_file = results_folder_path/f"model_poly_HVAC_{char_list[i]}.pkl"
        grid = joblib.load(target_file)
        # save grid search results

pd.DataFrame(pd.DataFrame(grid.cv_results_)).to_csv(results_folder_path.joinpath(f"gr
id_cv_result_poly_HVAC_{char_list[i]}.csv"))
        # grid search parameters
        param_grid = {
            'poly_degree': [1,2,3,4,5], # polynomial degrees
            'ridge_alpha': [0.001, 0.01, 0.1, 1.0] # L2 regularization
        }
        # best hyperparameters
        target_file =
results_folder_path/f"hyperparameters_poly_HVAC_{char_list[i]}.txt"
        content_to_write = f"{grid.best_params_}"
        target_file.write_text(content_to_write)
        # polynomial equation
        target_file = results_folder_path/f"equation_poly_HVAC_{char_list[i]}.txt"
        content_to_write = recover_model_equation(grid.best_estimator_, ['window_u',
'wall_r', 'roof_r', 'infiltration', 'lights', 'equipment', 'dhw'])
        target_file.write_text(content_to_write)
        # metrics on validation set
        y_pred = grid.best_estimator_.predict(X_test)
        target_file = results_folder_path/f"metrics_poly_HVAC_{char_list[i]}.txt"
        content_to_write = f"r2: {r2_score(y_test, y_pred)}"+f"\nmbe:
{mean_bias_error(y_test, y_pred)}"+f"\nmae: {mean_absolute_error(y_test,
y_pred)}"+f"\nrmse: {root_mean_squared_error(y_test, y_pred)}"+f"\nnmbe:
{normalized_mean_bias_error(y_test, y_pred)}"+f"\nnrmse:
{normalized_root_mean_squared_error(y_test, y_pred)}"
        target_file.write_text(content_to_write)
        # validation curves
        for param_name, param_range in param_grid.items():
            grid_ = grid
            train_scores, valid_scores = validation_curve(grid_.best_estimator_,
X_train, y_train, param_name=param_name, param_range=param_range, scoring="r2")
            train_mean = np.mean(train_scores, axis=1)
            valid_mean = np.mean(valid_scores, axis=1)

```

```

        plt.figure(figsize=(8, 5))
        plt.plot([str(p) for p in param_range], train_mean, label='Training
score')
        plt.plot([str(p) for p in param_range], valid_mean, label='Validation
score')
        plt.xlabel(f"{param_name}")
        plt.ylabel("R2 Score")
        plt.legend()
        target_file =
results_folder_path/f'validation_curve_poly_HVAC_{char_list[i]}_{param_name}.png'
        plt.ylim(0.95, 1.01)
        plt.savefig(target_file)
        # learning curve
        grid_ = grid
        LearningCurveDisplay.from_estimator(grid_.best_estimator_, X_train, y_train)
        target_file =
results_folder_path/f'learning_curve_poly_HVAC_{char_list[i]}.png'
        plt.ylim(0.95, 1.01)
        plt.savefig(target_file)
        #'''
        #'''
        # mlp
        # load model
        target_file = results_folder_path/f"model_mlp_HVAC_{char_list[i]}.pkl"
        grid = joblib.load(target_file)
        # save grid search results

pd.DataFrame(pd.DataFrame(grid.cv_results_)).to_csv(results_folder_path.joinpath(f"gr
id_cv_result_mlp_HVAC_{char_list[i]}.csv"))
        # grid search parameters
        param_grid = {
            'model__hidden_layer_sizes': [(50, 50), (100, 50), (100, 100)], # Small
to moderately deep networks
            'model__activation': ['relu', 'tanh'], # 'logistic' can be slow and less
effective for regression
            'model__solver': ['adam', 'lbfgs'], # 'lbfgs' is good for small
datasets; 'adam' works well generally
            'model__alpha': [1e-5, 1e-4, 1e-3, 1e-2], # L2 regularization
        }
        # MLP hyperparameters
        target_file =
results_folder_path/f"hyperparameters_mlp_HVAC_{char_list[i]}.txt"
        content_to_write = f"{grid.best_params_}"
        target_file.write_text(content_to_write)
        # metrics on validation set
        y_pred = grid.best_estimator_.predict(X_test)
        target_file = results_folder_path/f"metrics_mlp_HVAC_{char_list[i]}.txt"
        content_to_write = f"r2: {r2_score(y_test, y_pred)}"+f"\nmbe:
{mean_bias_error(y_test, y_pred)}"+f"\nmae: {mean_absolute_error(y_test,
y_pred)}"+f"\nrmse: {root_mean_squared_error(y_test, y_pred)}"+f"\nnmbe:
{normalized_mean_bias_error(y_test, y_pred)}"+f"\nnrmse:
{normalized_root_mean_squared_error(y_test, y_pred)}"
        target_file.write_text(content_to_write)
        # validation curves
        for param_name, param_range in param_grid.items():

```

```

        grid_ = grid
        train_scores, valid_scores = validation_curve(grid_.best_estimator_,
X_train, y_train, param_name=param_name, param_range=param_range, scoring="r2")
        train_mean = np.mean(train_scores, axis=1)
        valid_mean = np.mean(valid_scores, axis=1)
        plt.figure(figsize=(8, 5))
        plt.plot([str(p) for p in param_range], train_mean, label='Training
score')
        plt.plot([str(p) for p in param_range], valid_mean, label='Validation
score')
        plt.xlabel(f"{param_name}")
        plt.ylabel("R2 Score")
        plt.legend()
        target_file =
results_folder_path/f'validation_curve_mlp_HVAC_{char_list[i]}_{param_name}.png'
        plt.ylim(0.95, 1.01)
        plt.savefig(target_file)
        # learning curve
        grid_ = grid
        LearningCurveDisplay.from_estimator(grid_.best_estimator_, X_train, y_train)
        target_file =
results_folder_path/f'learning_curve_mlp_HVAC_{char_list[i]}.png'
        plt.ylim(0.95, 1.01)
        plt.savefig(target_file)
        #'''

```