

A COMPARISON OF BOTTOM-UP METHODS FOR ESTIMATING INSTITUTIONAL  
BUILDING ENERGY USE TO INFORM RESOURCE AND EMISSION REDUCTION  
STRATEGIES

by

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# A COMPARISON OF BOTTOM-UP METHODS FOR ESTIMATING INSTITUTIONAL BUILDING ENERGY USE TO INFORM RESOURCE AND EMISSION REDUCTION STRATEGIES

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## ABSTRACT

Bottom-up engineering models are an emerging approach for evaluating energy efficiency solutions at district or regional scales. More flexible than statistical models, bottom-up models allow planners to quantitatively evaluate energy efficiency and supply options, leading to more effective policies and energy demand solutions that better reflect our changing climate. This thesis compares two bottom-up methods for exploring resource and emission reduction strategies in the institutional sector: the *Wireframe* method and the *Reference* method. These methods are compared by predicting the annual consumption of post-secondary student residences in Southern Ontario and measuring the error of each, compared with the 2013 mandatory energy report data from the Ministry of Energy of Ontario. Both methods produced aggregate energy error ranges of 5% to 12% in a detailed analysis, suggesting that they are both effective for large-scale energy reduction studies.

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## **TABLE OF CONTENTS**

<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	Research Objective and Questions	3
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>5</b>
2.1	Mandatory Energy Reporting as a Data Source	6
2.2	Energy Benchmarking in Post-Secondary Buildings	7
2.3	Classification of Existing Building Stocks	9
2.4	Development and Characterization of Reference Energy Models	10
<b>3</b>	<b>METHODOLOGY</b>	<b>17</b>
3.1	Data Collection and Validation	19
3.2	Building Stock Classification	20
3.3	Building Stock Characterization	21
3.4	Building Stock Consumption Prediction	23
3.4.1	Reference Method Consumption Prediction	25
3.4.2	Wireframe Method Consumption Prediction	27
3.5	Model Tuning	29
3.6	Institutional Residence Building Stock Validation and Error Analysis	30
<b>4</b>	<b>DATA COLLECTION AND VALIDATION</b>	<b>31</b>
4.1	Data Validation for Colleges and Universities	32
4.2	Data Validation for College and University Building Operations	36
4.2.1	Building Operation Data Cleaning	36
4.2.2	Administrative Office Buildings – College Sample	37
4.2.3	Administrative Office Buildings – University Sample	39
4.2.4	Administrative Office Buildings – College and University Sample	41
4.2.5	College and University Benchmarking by Building Operation	42

<b>5</b>	<b>BUILDING CLASSIFICATION AND CHARACTERIZATION</b>	<b>44</b>
5.1	Cleaning of Data Sets	45
5.2	Building Stock Characterization	47
5.3	Student Residence Characterization Values	48
5.3.1	Form inputs: pre-1980 Lowrise residence models	48
5.3.2	Fabric inputs: pre-1980 Lowrise residence models	49
5.3.3	Program inputs: Space activity for pre-1980 Lowrise residence models	50
5.3.4	Program input: Occupant densities for pre-1980 Lowrise residence models	51
5.3.5	Program input: Ventilation rates for pre-1980 Lowrise residence models	51
5.3.6	Program input: Lighting loads for pre-1980 Lowrise residence model	52
5.3.7	Program input: Plug and process loads for pre-1980 Lowrise residence model	52
5.3.8	Program input: Water system rates for pre-1980 Lowrise residence model	53
5.3.9	Equipment input: HVAC system characteristics for pre-1980 Lowrise residence model	53
5.4	Additional Template Development	54
5.4.1	Post-1980 Lowrise	55
5.4.2	Post-1980 Midrise	56
5.4.3	Pre-1980 Highrise	60
<b>6</b>	<b>STUDENT RESIDENCE MODEL TUNING</b>	<b>64</b>
6.1.1	Pre-1980 Lowrise residence model adjustment	65
6.1.2	Post-1980 Lowrise residence model adjustment	67
6.1.3	Post-1980 Midrise residence model adjustment	69
6.1.4	Pre-1980 Highrise residence model adjustment	71
<b>7</b>	<b>ENERGY SIMULATION RESULTS</b>	<b>73</b>
7.1	Comparison of Reference and Wireframe Predictions	73
7.1.1	Pre-1980 Lowrise	74
7.1.2	Post-1980 Lowrise	77
7.1.3	Post-1980 Midrise	80
7.1.4	Pre-1980 Highrise	83
7.2	End-Use Energy by Building	86
7.3	Error Analysis	88
7.3.1	Pre-1980 Lowrise	88
7.3.2	Post-1980 Lowrise	89

7.3.3	Post-1980 Midrise	90
7.3.4	Pre-1980 Highrise	91
7.3.5	Random Sampling	92
<b>8</b>	<b>DISCUSSION</b>	<b>93</b>
8.1	Error Discussion	97
8.2	Future Research	98
8.3	Research Implications	98
<b>9</b>	<b>CONCLUSIONS</b>	<b>99</b>
<b>10</b>	<b>REFERENCES</b>	<b>100</b>
<b>APPENDIX A: POST-SECONDARY ENERGY BENCHMARKS BY BUILDING TYPE</b>		<b>107</b>
<b>APPENDIX B: REFERENCE BUILDING MODEL COMPARISON AND SOURCES</b>		<b>119</b>
<b>APPENDIX C: REFERENCE BUILDING MODEL CHARACTERIZATION TEMPLATES</b>		<b>155</b>
<b>APPENDIX D: RANDOM SAMPLING IN RSTUDIO</b>		<b>184</b>

## LIST OF TABLES

<b>Table 1.</b> Description of size categories used to classify Southern Ontario student residences...	21
<b>Table 2.</b> Description of vintage categories used to classify Southern Ontario student residences	21
<b>Table 3.</b> Building categories used to review commercial reference energy models	22
<b>Table 4.</b> Buildings reported under the same location for college residences	37
<b>Table 5.</b> Buildings with multiple operations after relevant data has been joined to form a building	37
<b>Table 6.</b> Initial sample of Administrative Office buildings considered for benchmarking study	38
<b>Table 7.</b> Administrative Office buildings results before outlier removal	38
<b>Table 8.</b> Administrative Office buildings after outliers have been removed	38
<b>Table 9.</b> Initial sample of University Administrative Office buildings considered for benchmarking study	39
<b>Table 10.</b> University Administrative Office buildings results before outlier removal	39
<b>Table 11.</b> University Administrative Office buildings after outliers have been removed	40
<b>Table 12.</b> Initial sample of university and college Administrative Office buildings considered for benchmarking study	41
<b>Table 13.</b> College and university Administrative Office buildings results before outliers are removed	41
<b>Table 14.</b> College and university Administrative Office buildings after outliers have been removed	42
<b>Table 15.</b> Samples derived from the classification process with average descriptors. Note that the post-1980 Lowrise category has the largest standard deviation as one of its buildings was identified as an outlier but not removed.	46
<b>Table 16.</b> Pre1980 Lowrise Form characterization inputs	48
<b>Table 17.</b> Pre-1980 Lowrise Residence Fabric characterization inputs for both, the Reference and Wireframe models	50
<b>Table 18.</b> Space activity breakdown for Lowrise residence reference models	50
<b>Table 19.</b> Occupancy density for pre-1980 Lowrise residence models	51
<b>Table 20.</b> Ventilation rates for pre-1980 Lowrise residence models	51
<b>Table 21.</b> Lighting rates for pre-1980 Lowrise residence models	52
<b>Table 22.</b> Plug and process loads for pre-1980 Lowrise residence models	52
<b>Table 23.</b> Water system rates for pre-1980 Lowrise residence models	53
<b>Table 24.</b> Post-1980 Midrise residence <i>fabric</i> inputs	55
<b>Table 25.</b> Lighting rates for pre-1980 Lowrise residence models	56
<b>Table 26.</b> Building Form comparison between DOE models and Midrise student residence values	57
<b>Table 27.</b> Programmatic breakdown of the Small Hotel and Mid-rise Apartment commercial reference models	58
<b>Table 28.</b> Pitman Hall space activity breakdown	58



<b>Table 29.</b> Space activity breakdown for Midrise Residence reference models .....	59
<b>Table 30.</b> Occupancy density for post-1980 Midrise residence models .....	59
<b>Table 31.</b> Building <i>form</i> comparison between DOE models and Highrise student residence values .....	61
<b>Table 32.</b> Space activity breakdown for Highrise residence reference models .....	62
<b>Table 33.</b> Occupancy density for post-1980 Midrise residence models .....	62
<b>Table 34.</b> Percentage error ranges for pre-1980 Lowrise buildings.....	76
<b>Table 35.</b> Percentage error ranges for post-1980 Lowrise buildings .....	79
<b>Table 36.</b> Percentage error ranges for post-1980 Midrise buildings .....	82
<b>Table 37.</b> Percentage Error ranges for pre-1980 Highrise buildings.....	85
<b>Table 38.</b> Percentage error and RMSE of pre-1980 Lowrise buildings.....	88
<b>Table 39.</b> Percentage Error and RMSE of post-1980 Lowrise buildings. ....	89
<b>Table 40.</b> Percentage error and RMSE of post-1980 Midrise buildings .....	90
<b>Table 41.</b> Percentage error and RMSE of pre-1980 Highrise buildings .....	91

## LIST OF FIGURES

<b>Figure 1.</b> This image shows how the <i>Reference</i> method predicts aggregate consumption. A simplified energy model is developed to represent a typology of buildings. After simulation, the area normalized consumption of the model is multiplied by measured areas of buildings with same typology to predict the aggregate energy consumption .....	17
<b>Figure 2.</b> For the <i>Wireframe</i> method, each building in the sample is modeled using its real geometry and orientation. The individual consumption is added to represent the aggregate load of the sample. ....	18
<b>Figure 3.</b> Flowchart summary of the development and evaluation of the <i>Wireframe and Reference</i> models.....	18
<b>Figure 4.</b> Building variables used to classify post-secondary buildings in this study (image from <a href="http://www.cgtrader.com">www.cgtrader.com</a> ) .....	20
<b>Figure 5.</b> Zoning example using the perimeter/core method .....	23
<b>Figure 6.</b> Process used to create 3D building geometry .....	24
<b>Figure 7.</b> Approach used to develop the energy demand of student residence reference models .....	25
<b>Figure 8.</b> Steps to predict consumption using the Reference method: 1) Collection of average building characteristics from a dataset of buildings, 2) Development of Reference model geometry (two orientations), 3) Allocation of weather file and characterization template, 4) Reference model simulation using Energy Plus, and 5) Area normalized consumption predicted from both models are averaged out and multiplied by the total conditioned floor area of the set of buildings.....	26
<b>Figure 9</b> Steps to predict consumption using the Wireframe method: 1) Collection of average building characteristics from a dataset of buildings, 2) Development of Wireframe model geometry, 3) Allocation of weather file and characterization template, 4) Simulation using	

Energy Plus, and 5) Individual building consumption are aggregated to represent the total consumption of the dataset of buildings. ....	28
<b>Figure 10.</b> This image describes the process of predicting the end-use consumption of a Reference model: (1) A Rhinoceros 3D model is created using geometrical characteristics of the building stock, (2) Characterization templates and weather data are applied to the 3D model using UMI, (3) The Reference model is simulated using Energy Plus, and (4) The end-use consumption of the model is then determined predicted. ....	29
<b>Figure 11.</b> Climate Zone 5 (NECB 2011) and cities where MER institutional data was collected ..	31
<b>Figure 12.</b> EUI of selected college and university institutions.....	32
<b>Figure 13.</b> Mean and median EUI derived from the MER college/university category compared to the 212 ekWh/m <sup>2</sup> (Energy Star) and the 264 ekWh/m <sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies.....	33
<b>Figure 14.</b> Mean and median EUI derived from the college sample compared to the 212 ekWh/m <sup>2</sup> (Energy Star) and the 264 ekWh/m <sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies.....	34
<b>Figure 15.</b> Mean and median EUI derived from the MER university sample compared to the 212 ekWh/m <sup>2</sup> (Energy Star) and the 264 ekWh/m <sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies.....	35
<b>Figure 16.</b> College Administrative Office buildings considered to develop the sample's EUI .....	39
<b>Figure 17.</b> University Administrative Office buildings considered in the developed benchmark	40
<b>Figure 18</b> College and university Administrative Office buildings considered in the developed benchmark .....	42
<b>Figure 19.</b> Developed Energy Benchmarks for College and University building operations.....	42
<b>Figure 20.</b> Developed MER Benchmarks of Administrative, Residence, and Recreational facilities are compared to SCIEU Energy Star Portfolio Manager Laboratory benchmark is compared to MER laboratories. ....	43
<b>Figure 21.</b> Student residence segmentation using building size and vintage as variables. The number of buildings in the master dataset within each category are indicated in parentheses.	44
<b>Figure 22.</b> Quarryview residence (left) was removed due to its typology difference and resultant low EUI compared with the remaining post-1980 Lowrise dataset .....	45
<b>Figure 23.</b> Building geometry and shading devices from U.S. DOE models (from left to right): Midrise Apartment, Small Hotel, Large Hotel and Highrise Apartment.....	47
<b>Figure 24.</b> Pre1980 Lowrise Residence buildings showing typical flat roof condition .....	49
<b>Figure 25.</b> Post-1980 Midrise buildings compared to post-1980 Large Hotel (top) and 2004 Highrise DOE models.....	57
<b>Figure 26.</b> Pre-1980 Highrise buildings compared to pre-1980 Large Hotel (top) and 2004 Highrise DOE models.....	61
<b>Figure 27.</b> Visual representation of student <i>Reference</i> method models created with Rhinoceros and UMI.....	64
<b>Figure 28.</b> End-use comparison of reviewed DOE models and developed residence models. Cooling, lighting, and equipment EUIs predicted with the baseline template are all between the	

EUI reported for the hotel and the apartment models, therefore, only the water systems end-use was adjusted.....	65
<b>Figure 29.</b> The predicted EUI of the adjusted pre-1980 Lowrise model is 17% lower than the EUI benchmark of the pre-1980 Lowrise dataset quantified at 397 ekWh/m <sup>2</sup> .....	66
<b>Figure 30.</b> Differences between pre-1980 Lowrise adjusted model and the pre-1980 Midrise Apartment model are seen in heating, equipment and lighting uses .....	66
<b>Figure 31.</b> End-use comparison of reviewed DOE models and developed student residence models. Baseline heating EUI is larger than the heating EUI of both DOE models while water system EUIs is lower than both DOE models.....	67
<b>Figure 32.</b> The predicted EUI of the adjusted post-1980 Lowrise model is 7 % lower than the EUI benchmark of the post-1980 Lowrise Category quantified at 339 ekWh/m <sup>2</sup> .....	68
<b>Figure 33.</b> Adjusted post-1980 Lowrise and post-1980 Midrise Apartment end-use breakdown	68
<b>Figure 34.</b> Comparison of the end-use EUIs predicted with reviewed DOE and developed residence models. ....	69
<b>Figure 35.</b> The predicted EUI of the adjusted post-1980 Midrise model is 9% lower than the EUI benchmark of the post-1980 Midrise Category quantified at 312 ekWh/m <sup>2</sup> . ....	70
<b>Figure 36.</b> Adjusted post-1980 Midrise breakdown is most like the 2004 Highrise model. ....	70
<b>Figure 37.</b> Comparison of the end-use EUIs predicted with reviewed DOE and developed residence models. ....	71
<b>Figure 38.-</b> The predicted EUI of the adjusted pre-1980 Highrise model is 9% lower than the EUI benchmark of the pre-1980 Highrise Category quantified at 388 ekWh/m <sup>2</sup> . ....	72
<b>Figure 39.</b> The adjusted pre-1980 Highrise predicted energy breakdown is most like the 2004 Highrise model. ....	72
<b>Figure 40.</b> Building images and corresponding <i>Wireframe</i> method models for the pre-1980 Lowrise category .....	74
<b>Figure 41.</b> Pre-1980 Lowrise Heating comparison.....	75
<b>Figure 42.</b> Pre-1980 Lowrise Electricity comparison .....	75
<b>Figure 43.</b> Pre-1980 Lowrise Total Energy comparison .....	75
<b>Figure 44.</b> Pre-1980 Lowrise Area comparison. The simulated area for the Reference model does not change as the displayed area is the one used to predict the Reference EUI which is then scaled by multiplying by the measured area of the buildings. ....	75
<b>Figure 45.</b> Building images and corresponding Wireframe method models for the post-1980 Lowrise category .....	77
<b>Figure 46.</b> Post-1980 Lowrise Heating comparison .....	78
<b>Figure 47.</b> Post-1980 Lowrise Electricity comparison.....	78
<b>Figure 48.</b> Post-1980 Lowrise Total Energy comparison .....	78
<b>Figure 49.</b> Post-1980 Lowrise Area comparison .....	78
<b>Figure 50.</b> Building images and corresponding <i>Wireframe</i> method models for the post-1980 Midrise category .....	80
<b>Figure 51.</b> Post-1980 Midrise Heating comparison .....	81
<b>Figure 52.</b> Post-1980 Midrise Electricity comparison .....	81

<b>Figure 53.</b> Post-1980 Midrise Total Energy comparison .....	81
<b>Figure 54.</b> Post-1980 Midrise Area comparison .....	81
<b>Figure 55.</b> Building images and corresponding <i>Wireframe</i> method models for the pre-1980 Highrise category .....	83
<b>Figure 56.</b> Pre-1980 Highrise Heating comparison .....	84
<b>Figure 57.</b> Pre-1980 Highrise Electricity comparison .....	84
<b>Figure 58.</b> Pre-1980 Highrise Total Energy comparison .....	84
<b>Figure 59.</b> Pre-1980 Highrise Area comparison .....	84
<b>Figure 60.</b> Pre-1980 Lowrise predicted energy end-use by building.....	86
<b>Figure 61.</b> Post-1980 Lowrise predicted energy end-use by building .....	86
<b>Figure 62.</b> Post-1980 Midrise predicted energy end-use by building .....	87
<b>Figure 63.</b> Pre-1980 Highrise predicted energy end-use by building .....	87
<b>Figure 64.</b> Average total energy error rate against sample size.....	92
<b>Figure 65.</b> Heating Percentage Error produced by each category using Wireframe and Reference methods .....	94
<b>Figure 66.</b> The Pond residence was modelled as two independent buildings rather than one. .	95
<b>Figure 67.</b> Stack effect pressure variability in buildings of different heights [73] .....	96

## **LIST OF ABBREVIATIONS**

ACEEE	American Centre for an Energy Efficient Economy
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BEM	Building Energy Models
CES	Commercial Energy Survey
DOE	Department of Energy
EIA	Energy Information Administration
EUI	Energy Use Intensity
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
IEA	International Energy Agency
LBL	Lawrence Berkeley Laboratory
LBNL	Lawrence Berkeley National Laboratory
MER	Mandatory Energy Reports
MOE	Ministry of Energy
NREL	National Research Energy Laboratory
PNL	Pacific Northwest Laboratory
PNNL	Pacific Northwest National Laboratory
SCIEU	Survey of Commercial and Institutional Energy Use
TABULA	Typology Approach for Building Stock Energy Assessment
UBEM	Urban Building Energy Models

# 1 Introduction

The issue of energy efficiency has never been more pertinent. With climate change threatening every part of our planet and the urban population expected to surpass six billion by 2045 [1], we are in growing need of innovative solutions that will carry us into a sustainable future. Many countries across the globe have started by setting ambitious carbon reduction targets. The Government of Canada has committed to reducing its carbon emissions by 17% below 2005 levels by the year 2020. This target presents challenge as projected emissions are currently 17% above 2005 levels [2]. Because buildings are the largest energy consuming sector in the world and account for over 30% of total final energy consumed [3]; achieving energy and emissions reductions in the building sector is critical to meet short and long-term carbon reduction targets, therefore progressive designs and action plans are needed to create responsible urban spaces. Governments will look to designers and planners to provide them with solutions that reduce energy consumption and lower emissions caused by the built environment. In Canada, the commercial and institutional building sector accounts for 12% of energy consumption and 11% of CO<sub>2</sub> emissions [4]. More than 80% of Canadian buildings are over 15 years old and have been built to meet much lower energy efficiency requirements when compared to new construction [5], making them relatively inefficient. While the introduction of new efficient buildings helps to reduce environmental impact, the demolition and reconstruction of existing buildings is non-ideal due to their embodied energy. Therefore, energy conservation in existing buildings is critical to achieving Canada's 2020 and future goals of CO<sub>2</sub> emissions reduction. The challenge is to determine scenarios that will benefit most from retrofit actions as well as policies and incentives that will produce greater strides to more eco-friendly cities

In addition to Federal and Provincial Government targets, a cross-sector public-private collaborative from Toronto has committed to reduce 50% of the district's emissions by 2030 [6]. As buildings represent a substantial portion of these emissions, progressive cities like Toronto aiming to meet ambitious targets need tools that help designers and policy makers plan both more strategically and efficiently. The reduction of carbon emissions caused by the operation of buildings can be achieved in many ways including: benchmarking building consumption, retrofitting existing buildings, evolution of energy codes, and/or by decarbonizing energy sources. Benchmarking building consumption serves as an assessment of a building's performance; a

fundamental starting point to achieving energy reductions from the building sector and allows buildings to be compared against others of a similar vintage and operation. Studies show that buildings that benchmark their consumption tend to reduce their energy cost by 7% in a period of three years [7]. Using energy from sources with low emission processes, such as nuclear, hydro, or renewables, is key to achieving projected carbon reductions. Although Ontario has a low-carbon grid, it still uses natural gas and this source of energy does not seem to be phasing out any time soon. According to the International Energy Agency a combination of energy reduction, use of renewable energy, and decarbonizing power sources will be the main drivers for decreasing global carbon emissions caused by the building sector [3].

For Canada and cities like Toronto to achieve significant reductions in carbon emissions, researchers, planners, and developers must understand in detail the conditions of their buildings and the effects of implementing different policies and incentives. This type of analysis can be realized via *top-down* or *bottom-up* building stock energy models [8]. Top-down models utilize measured sector energy and appropriate variables to attribute energy consumption to characteristics of the stock. *Top-down* models consider the sector as an energy sink. They can determine the effect on energy consumption due to changes within the sector, however they cannot distinguish energy consumption from individual end-uses. The lack of detail regarding individual end-uses limits the capability of top-down models to identify areas of improvement for energy efficiency. Bottom-up building stock energy models are more detailed and can identify the contribution of each end-use towards an aggregated energy consumption. A common bottom-up approach for evaluating consumption at large scales involves classifying a building stock into reference models and characterizing them based on details of the existing stock. Bottom-up models require information from a building stock to predict consumption. This information includes building materials, equipment efficiencies, occupancy schedules, and internal loads. While this data can be obtained for a small group of buildings through audits, such collection becomes impractical for large scale studies. For this reason, bottom-up models utilize reference models to represent buildings at district or regional scales. After reference models are defined, a simulation is used to predict energy consumption and results are typically validated by comparing them to aggregate measured consumption. Although previous work has demonstrated the usefulness of reference models to explore energy and carbon emission strategies [9], there is no agreement on how such models should be defined [10].

This thesis compares two bottom-up methods, referred to as the *Wireframe Method* and the *Reference Method*, for exploring resource and emission reduction strategies in the institutional sector. Both methods consider average characteristics of a building sample as inputs but differ in their treatment of geometry. The *Reference Method* simulates the consumption of a single representative building, normalizes the result based on the area of the building, and multiplies the normalized consumption by the total conditioned area of the buildings intended to be studied to predict an aggregate consumption. The *Wireframe Method* uses geometric and orientation characteristics from all sample buildings to predict individual consumption which is then aggregated to represent the overall energy consumption of a sample.

The *Reference Method* is based on the approach used by the U.S. Department of Energy (DOE) to assess regional consumption studies [11], while the *Wireframe Method* is based on the approach used by MIT Sustainable Design Lab to predict the aggregate consumption of the city of Boston [12]. Both the U.S. DOE and MIT research labs used building audits, surveys and engineering judgement for the development of reference models. In this thesis, it was not possible to replicate this degree of background research; instead, pre-existing reference models were adapted to create a preliminary university residence model to test the relative performance of these methods. Several publicly available data sources were used to adjust this preliminary model, but it should be noted that significant additional research would be required to create a generalizable reference model for this typology.

## **1.1 Research Objective and Questions**

The objective of this research is to compare the Wireframe and Reference Methods to understand the degree to which the consideration of individual building form affects the energy prediction accuracy. This will be explored through the following research questions:

1. How do the energy predictions between the two methods compare to one another and to the measured consumption?
2. How does the aggregate consumption prediction error change when different sample sizes are considered?
3. To what extent is there benefit to modeling the individual building geometry in a large-scale model?



The hypothesis of this research is that the *Wireframe* method will provide better prediction accuracies and lower error rates for building categories with lower thermal performance and higher geometrical complexity. These results are expected as buildings with high performance envelopes and compact form retain indoor conditions better, thus decreasing the impact that shape and orientation can have on conditioning consumption. The analysis of predicted consumption and their errors will help inform which method is better according to the characteristics of a building stock.

## 2 Literature Review

Building Energy Models (BEMs) are recognized as an effective tool to optimize building energy consumption. BEMs can be used to quantify energy profiles, test different HVAC systems, evaluate the effect of building shape, measure the impact of proposed lighting strategies, or allow planners to quantitatively evaluate energy efficiency and supply options which lead to more effective policies and energy demand solutions. One of the challenges that these models encounter is that they require detailed building characteristics for their development. In many cases energy consumption measurements are necessary to validate the models. This type of data can take considerable effort to obtain and makes the development of energy models an expensive investment. One approach to characterizing BEMs utilizes average building descriptors. These are typically based on data collected from existing standards, surveys, case studies, and/or building audits. The quality of the inputs is strongly influenced by the number of case studies, surveys, or audits used in their development and by the number of buildings to be represented. The closer the sample size is to the number of buildings represented, the fewer problems of selection and representation are encountered [13].

BEMs characterized by average building descriptors will be referred to as “reference models” throughout this thesis. These have been used to measure improvements in energy codes [14], assess regional cool storage potential [15], measure cogeneration potential in the commercial building sector [15], and more recently to predict district energy demands using geospatial datasets [12]. The first step to developing reference models for large scale studies involves the classification of a building stock into samples using descriptive building variables such as operation, construction period, and form. The developer must then determine the number of reference models that will adequately represent the building stock. Reference models are then characterized using average building descriptors, for example materials and glazing ratio, collected from the classified samples. Additional inputs such as internal loads and occupancy can be derived from building audits, surveys, existing literature, and engineering judgment. Once reference models have been characterized, simulations are performed to predict their end-use consumption. Results from the models are then extrapolated to represent all buildings part of the classified samples. Simulation outputs should be validated by comparison with measured consumption data to ensure they accurately represent the consumption of the sample. Each of the steps regarding the development

process of a reference energy model varies according to a model's purpose and availability of data. The approach explained above has been used by the U.S. DOE and other U.S national labs and is the foundation of one of the methods that this thesis will evaluate. A more detailed explanation of previous efforts for reference model development to predict aggregate consumption will be discussed in this review.

The following sub-sections summarize the academic literature to date related to energy disclosure and benchmarking in post-secondary buildings, classification of existing buildings and reference model development. *Mandatory Energy Reporting as a Data Source* (Section 2.1) reviews Ontario's existing energy disclosure regulation. *Energy Benchmarking in Post-Secondary Buildings* (Section 2.2) discusses existing benchmarking studies and their limitations. The studies presented in Section 2.2 will later be compared to Ontario Mandatory Energy Report consumption data. *Classification of Existing Building Stocks* (Section 2.3) reviews approaches and variables used by other researchers to classify building stocks. The studies presented in Section 2.3 will inform the approach and classification variables that will be used to segment Ontario post-secondary buildings. *Development and Characterization of Reference Energy Models* (Section 2.4) will present a chronological review of previous reference model development methods including their purpose and limitations. These methods will be reviewed to identify sources for characterization data, how simulation outputs were validated and differences among their development.

## **2.1 Mandatory Energy Reporting as a Data Source**

In 2009, Ontario's Ministry of Energy (MOE) implemented Regulation 397/11 [16] under the Green Energy Act. This regulation requires municipal, post-secondary, and healthcare buildings to annually report their energy consumption, carbon emissions, building operations, and some characteristics that influence a building's energy consumption. The resultant mandatory energy reporting (MER) data can be used to collect building descriptors such as building operation, location and consumption. At present, the MOE does not validate reported data from the public sector. To use this data to develop reference models for large-scale studies requires that its reliability be verified through comparison to national benchmarks. Those buildings that compare

well to national average are assumed to be valid and can be used to develop institutional reference models.

Further, although extremely helpful in the development of reference models, MER data does not contain key information necessary to inform bottom-up model predictions, such as building vintage. The building's vintage informs assumptions about construction methods and materials (affecting the thermal resistance and air-tightness of the building envelope) and the age and type of appliances (contributing to electricity consumption and internal heat gains). Additional Building descriptors needed for reference model development such as construction period, number of floors, glazing ratio, and building height must be obtained from other sources, which include Geographical Information Systems (GIS), online documents, campus maps, and visual judgment. Operation descriptors such as occupancy schedules, equipment efficiencies, internal loads, and other can be derived from DOE commercial reference models as these can have similar operations to those seen in the institutional sector and are based on national surveys or audits. While this approach to develop reference energy models is not ideal (as it is not based on institutional building audits or surveys), it is an effective way to address data limitations. Building form is also widely understood to significantly affect performance, with some energy codes prescribing higher R-values for less compact buildings as a result [17].

## **2.2 Energy Benchmarking in Post-Secondary Buildings**

The term building energy benchmark began to be used in the 1990's as a comparative of a building's energy performance to the performance of other buildings with similar characteristics [18]. Benchmarking a building's performance is not prioritized in the real estate market due to lack of information about building energy use, however benchmarking a building has shown to produce not only environmental benefits but improvements in the overall performance of buildings [19]. In the *San Francisco Existing Commercial Buildings Performance Report* [20] the authors found a relationship between energy efficiency and energy benchmarking. In their report, commercial buildings that complied with the city's benchmark regulation were able to reduce their energy use by 7.9% and 17% of their GHG emissions over three years. In addition, a survey [21] conducted by the American Centre for an Energy Efficient Economy (ACEEE) found that 62% of utility

customers in California that benchmarked their buildings changed their energy consumption habits upon realizing how their building compared to others.

Benchmarking data is a key component in energy consumption reductions at greater scales. Although North American national laboratories have developed datasets that include building use, size, climate and energy use, there is a lack of granular data to compare post-secondary building consumption. Since 2000, the Office of Energy Efficiency in Canada has published several energy benchmark surveys. The *Consumption of Energy Survey* (CES) was the first survey to include all provinces, focusing only on Canada's universities, colleges, and hospitals. In the years following, CES expanded to cover nearly all segments of the commercial and institutional sector. In more recent Canadian surveys, such as *Survey of Commercial and Institutional Energy Use – 2009* [22], post-secondary buildings are included in the “other” category. This shift makes comparing consumption benchmarks for institutional building operations a challenging task as all post-secondary operations are now part of the same “other” category alongside entertainment, shopping centres and leisure buildings. Although this limits the possibility of obtaining granular consumption benchmarks to compare post-secondary buildings, there are several commercial building benchmarks with operations comparable to those found in post-secondary institutions, including office and lodging operations. Like [22], *Energy Star Portfolio Manager* serves as an energy benchmarking tool. More than 40 percent of U.S. commercial building space is already benchmarked in Portfolio Manager and has been recently adopted by the Canadian Government as the platform for the Nation's energy benchmarking program [23]. In 2016, Energy Star Portfolio Manager released a technical reference report that presents median energy use intensity (EUI) by building operation for many Canadian commercial and institutional buildings [24]. Although this reference report includes a nationwide “university/college” benchmark, it does not have the granularity required to evaluate post-secondary buildings consumption by operation, as all university and college buildings are included in the same category. The Energy Star reference report only contains national consumption averages, which are too general when aiming to compare buildings in a specific climate. Nonetheless, the report does have commercial building benchmarks with operations comparable to those found in post-secondary institutions, such as recreational, lodging/residential, laboratories and administrative office operations.

The ideal benchmark survey to validate MER data is one that reports post-secondary consumption by building operation and is representative of a specific climate. A benchmarking study [25] done for the University of Massachusetts Amherst does this. In total, 100 university buildings (833,919 m<sup>2</sup>) were considered to develop the university benchmarks. Although the study groups post-secondary buildings by their operation (*i.e.* administrative, residential, laboratories), the developed benchmarks are based only on buildings part of one university. While [22, 24] considered buildings from multiple institutions and climates, they do not allow for a granular comparison as neither has developed benchmarks specific for post-secondary operations. The benchmarks developed in [25] have the operation granularity but are limited as only one university was considered in their development.

To validate Ontario MER data, commercial building operation benchmarks from [22, 24] will be used as they are based on nationwide studies and consider commercial buildings with similar operations to the ones seen in the institutional sector. However, [22] will be the main source of comparison as this study presents consumption benchmarks for buildings within Ontario.

## **2.3 Classification of Existing Building Stocks**

To develop large-scale bottom-up models, an existing stock must first be classified into sets based on building typologies and represented with *reference models* using descriptive building variables that have the largest impact on their energy consumption. The modeller must determine the appropriate number of reference models required to accurately represent the building stock that will be analyzed. Defined reference buildings must be capable of representing the majority of the existing building stock, be compatible with available data, and suit the intended purpose and scope of the study. While using more detailed classifications based on descriptive building variables (*i.e.* form, vintage, height) improves the accuracy of the classification, this approach decreases sample sizes within each set and increases the level of effort and model complexity due to the increased number of reference models required. Determining the right set of reference models is therefore a critical challenge in large-scale model development. This section provides an overview of previous classification studies to determine how this challenge has been addressed.

In recent decades, several approaches to define building typologies have been used in European countries to represent their residential stock. The Typology Approach for Building Stock

Energy Assessment (TABULA) examined these different approaches and derived a concerted method to develop residential building typologies for European countries [26]. The TABULA project has been used to classify existing residential buildings in over fifteen countries including Italy, Sweden, Norway, Spain, and Great Britain. TABULA classifies buildings according to their location, age, and geometry (shape/volume); this has proven to be successful at determining typical energy consumption values for existing buildings even in different climates.

Dall'O *et al.* [27] developed a methodology based on cartographic documentation, thematic maps, and geometric data to classify the energy performance of residential buildings on an urban scale. Their method allows the development of quick pre-energy certifications of buildings in a desired region by defining sample buildings (based on construction period and surface to volume ratio) and performing energy audits on them. The authors' methodology was tested on a residential building stock in Carugate, Italy, therefore operation type and location climate were also considered in the classification process.

Panayiotoua *et al.* [28] evaluated different building characteristics and their impact on the energy consumption using the residential building stock of Cyprus. 500 residential buildings were classified according to their climate zone, type, age, and size. Additional parameters, such as time of occupancy use, occupant salary, and heating systems were also used to assess their contribution to building energy use.

Benejam *et al.* [29] represented the Spanish building stock with 120 reference buildings corresponding to six building categories. The reference buildings used were classified by collecting data on overall characteristics of the Spanish building stock. The same variables: operation type, climate, and construction period were used to segment the existing building stock.

The above methods for classifying building stock have informed the approach used in this thesis to classify Ontario post-secondary buildings: building location, operation, vintage, and size will therefore be used to segment Ontario's post-secondary building stock into categories.

## **2.4 Development and Characterization of Reference Energy Models**

In 1983, the Pacific Northwest Laboratory (PNL) published a group of reference models to represent commercial buildings in the U.S [14]. This set was intended to issue a baseline for

energy conservation standards and their improvement to advance the design of new commercial and residential buildings. The study covered office, retail, elementary, apartment, hotel, warehouse, restaurant and hospital buildings in five climates. The models were characterized based on ASHRAE/IES Standard 90A-1980 recommendations, physical building characteristics collected from selected sample buildings considered typical for the desired operation, and schedules defined by Building Energy Performance Standards. A simulation of the developed reference models was performed using DOE energy simulation program however the simulated energy use was not validated to measured data. In following years, reference models were developed considering a larger variety of existing buildings through small and large-scale surveys.

In 1986, the Synergic Resource Corporation developed a set of simple regional reference energy models to analyze Florida's building energy use in a cool storage assessment study, which included eleven building types and eight energy end-uses [15]. The end-use estimates were based on data from 1200 Florida buildings, energy standard recommendations, and engineering studies. The reference models developed represented offices, retail spaces, schools, higher education, hospitals, hotels, restaurants, and other Florida service buildings and were calibrated against total aggregate annual energy use data.

In 1987, XEnergy Incorporated developed a set of six reference buildings to represent office, lodging, healthcare, retail, supermarket, and school buildings in New York State. The models were used to study energy end-uses and conservation potential in existing buildings (referenced in [11]). Developed models were based on data collected from surveys performed on 184 buildings in New York. The models were simulated in DOE and resulted in seven end-uses.

In 1988, an algorithm to disaggregate commercial whole building hourly electrical loads into end-uses was presented by Lawrence Berkeley Laboratory (LBL) [30]. The End-use Disaggregation Algorithm (EDA) was developed from the analysis of electric-load data taken at 15-minute intervals from selected Southern California buildings, audits, weather data, and simulation results. The primary component used in the EDA is the regression of measured hourly loads as a function of outdoor dry bulb temperature. A regression was performed at a measured temperature to calculate the nominal load of the building. This regressed building load was then divided into two categories, temperature-dependent loads (building conditioning) and temperature-



independent loads (lighting, miscellaneous, *etc.*). A base temperature (based on the temperature-independent loads) and data gathered from audits were then used to characterize simulation models. The energy models were simulated, and end-use fractions were obtained. End-uses were developed with these fractions and adjusted so that they would sum to the actual measured loads. The conditioning end-use is the only variable composed of both temperature-dependent and temperature-independent elements. Note that this algorithm only applied to buildings in cooling mode.

In 1988, Persily [31] used commercial and institutional air tightness data from 139 buildings to assess the impact that building operation, wall construction, number of stories, and construction period have on envelope leakage. The buildings in his report included office towers, schools, retail stores, and other typologies across several locations in the United States, Canada, Sweden and the United Kingdom. The mean ages of these buildings ranged from 20 to 30 years and they varied in height and construction assemblies. Due to the small sample size, no conclusions could be drawn regarding the effect that the selected building variables had on air tightness, however results suggested that frame walls and Low-rise buildings tended to have higher infiltration rates. The results from the paper were presented as airflow rates at a pressure difference of 75 Pa, normalized by the surface area of the building envelope. Results from this study are now used to characterize the airtightness of some DOE reference energy models.

In 1989, LBL established a methodology to develop DOE reference models for Southern California. Nine reference building models were created to represent offices, retail stores, supermarkets, restaurants, schools, health clinics, and refrigerated and non-refrigerated warehouses [32]. Developed reference models were based on ASHRAE standards, 337 on-site surveys, mail surveys, and one year of hourly whole-building load data from 794 billing accounts. The on-site surveys were performed on Southern California buildings to collect characteristics such as number of floors, area, shading, windows, vintage, location, occupancy hours, and building operation. These variables were used to characterize the DOE models and hourly measured datasets were used to calibrate and validate the results. The inability to capture the diversity of starting and stopping times found in commercial stocks is noted as a limitation of this study.

In 1991, LBL and the Gas Research Institute (GRI) developed 481 reference models including hospitals, school/college, prisons, hotels, restaurants, offices, supermarkets, apartments,

and retail stores [11]. These models were created as a market assessment tool that would analyze the potential of cogeneration in commercial buildings. The models represent 13 major U.S. cities and were characterized based on size of buildings, operation type, location, vintage, and equipment. Three vintages were defined: stock vintage (pre-1981), current vintage (1981-1988) and average vintage (all vintages). Characterization information was derived from extensive analysis of data from the Energy Administration Agency, sector-specific data for hospitals and schools, and 20 engineering studies from across the nation. Output files of the DOE simulation included hourly heating, cooling, electricity, and total loads. Hourly energy profiles were simulated using DOE, however only annual energy use intensities were calibrated against statistical data due to the scarcity of measured hourly load shapes. This study is the basis of existing U.S. DOE commercial reference models.

In 1994, LBL introduced an innovative approach to estimate end-use load shapes and energy use intensities [33]. The novelty of this research was the calibration of estimated end-use load shapes with measured whole-building load-shape data using the EDA described in [30]. The initial end-use estimates were developed using on-site surveys of about 800 buildings and mail surveys of over 6000 accounts. HVAC end-uses and (heating, cooling, and ventilation) resulted from simulations of the models, and non-HVAC end-uses were estimated from engineering analysis of data on reported schedules and installed capacities. Whole-building electricity load shapes were developed from two main sources: 1) Load research data (to develop reference whole-building load *shape*) and 2) Commercial sector EUIs by building type (to determine the *magnitude* of the load). The EDA methodology was then used to finalize the reconciliation process. However, the advantages of developing complex load shapes were unclear.

In 1999, Huang and Franconi reviewed existing reference models from 17 engineering studies to develop a set of reference energy models to evaluate the contributions of different building components to buildings heating and cooling loads [34]. Building descriptions were separated into three categories: 1) Physical building characteristics, 2) HVAC system characteristics and 3) Building internal conditions and operational patterns. The authors highlight the limitation of model reconciliation in existing reference models, listing the following reasons: 1) scarcity of detailed measured data, 2) large variation of energy use among any collection of buildings, and 3) multiple degrees of freedom in the calibration. This paper defines 36 reference

models which include two vintages and two (north and south) climatic regions within the United States. Most internal conditions and operating schedules were taken from the LBL/GRI work [11]. Physical building characteristics, and end-use intensities were updated based on the 1989 CBECS. Simulated annual building energy uses were compared to published governmental estimates and revealed significant differences.

In 2006, NREL published a set of 22 benchmark models created in Energy Plus that could be simulated in nine locations [35]. These reference models were built to be representative of new commercial buildings built to meet minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004. Previous reference models [11, 32, 33] focused on characterizing energy use in existing buildings, while the NREL models were developed to aid in the development of more efficient design guides. These models are based on data from the *2000 Census* [36], *2002 Economic Census* [37], *2003 CBECS* [38], and 2005 construction cost data [39].

In 2009, Swan and Ugursal [8] presented an up-to-date review of several approaches used for top-down and bottom-up modeling energy use. Two distinct bottom-up approaches are identified to evaluate the energy consumption of specific end-uses: *Statistical methods* (rely on historical energy data, building descriptors, and regression analysis) and *Engineering methods* (built on power ratings, use of equipment, systems, occupancy schedules, and building physics). Bottom-up models commonly require information of the built stock including building geometry, appliances, climate, occupancy schedules, and consumption. Statistical models use this and other data (socioeconomic, historical energy consumption, *etc.*) to regress energy consumption as a function of house characteristics. *Statistical methods* can separate the effect of occupant behaviour, a variable known to have a significant effect on results from engineering methods [40]. *Engineering methods* (EM) are the most flexible and capable of testing new technologies that have no historical consumption data, however occupant behaviour has to be defined. Three EM approaches are described in this paper: (1) distributions, (2) archetypes, and (3) sampling. The first utilizes distributions of appliance ownership and use with power ratings to calculate the energy consumption of each end-use. A limitation of this approach is that it does not account for interactions amongst end-uses. The second classifies the housing stock according to vintage, size, type, and more (archetypes). Modeling inputs are taken from descriptors of each house class. Simulated consumption is then scaled up to be representative of the regional or national housing

stock. The third approach defines its modeling inputs from sample houses. The variety of houses in the stock require large databases of representative dwellings, and this is a limitation of this technique. The most apparent drawback of bottom-up *Engineering methods* is that occupant behaviour must be assumed by the modeller, and this can significantly alter the energy simulation results. In comparison, the drawback of bottom-up *Statistical methods* is their inability to model the impact of different energy conservation strategies. The Swan and Ugursal thus suggest “hybrid models”, combining engineering methods with statistical models to address these limitations.

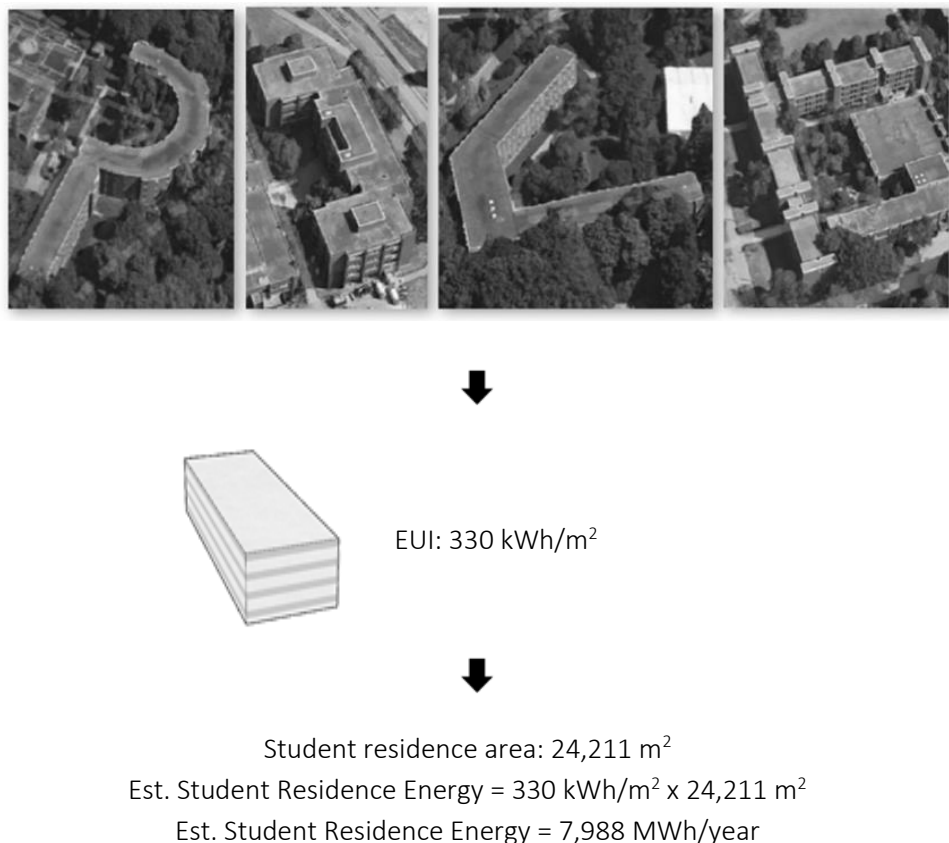
In 2015, Cerezo, Sokol, Reinhart and Al-Mumin [41] presented three methods for characterizing reference models – for Urban Energy Simulations. A residential area in Kuwait City was selected to evaluate the characterization methods. The studied neighborhood had 200 houses with several vintages and 140 measured yearly consumptions. The three methods identified by the authors: 1) Available literature, 2) Local expertise, and 3) Probabilistic occupancy parameters. The first assumes one archetype for all buildings that share the same use. The characterization is done deterministically based only on available literature. The second approach classifies the stock using parameters such as vintage and size. For this study only vintage was used, dividing the stock into four categories. This method uses knowledge of local construction and engineering practices, and documentation of representative sample buildings for each archetype. Window to wall ratios are assessed through photography analysis. Occupancy, plug loads, and lighting power density schedules are based on surveys and average room sizes. The third approach reduces the level of uncertainty due to occupant behavior by using probabilistic estimation that assumes that all unknown parameters have uniform distributions. The main difference with this approach is that probability distributions are assigned to uncertain parameters in the model such as occupancy, lighting, plug loads, and set-point temperatures. The model works by first defining the unknown parameters and their acceptable limits. A parametric analysis is performed for each building in the sample through urban energy simulations. The results from simulations are compared to measured data to quantify the error and test the assumption. This method required 640 simulations for each of the studied residences. 105 out of 140 buildings found one or more combinations of parameters that matched the measured EUI. The results show that the third method achieved a 30% reduction in error from the standard deviation when compared to the EUI distribution. Therefore, the Probabilistic approach was more accurate at predicting individual building consumption, albeit with a significantly more intense process.

In 2016, Cerezo, Reinhart and Bemis [12] presented a “bottom-up” approach taken to develop an UBEM that represents the city of Boston. Bottom-up models are typically based on building data processed analytically, statistically, or both. Statistical models link measured building energy use to building descriptors via regression models [42, 43]. Since they are based on measured data, statistical approaches are effective at incorporating occupant behavior, a problem encountered in analytical models [44]. On the other hand, statistical models are unable to simulate the impact of several energy efficiency measures in buildings. A workflow for the generation of urban building energy demand models (UBEM) using existing geospatial datasets was introduced as a solution to statistical model limitations. The novelty of this UBEM archetype approach is the use of GIS shapefiles to characterize building geometry on a case by case basis. GIS and Property Tax Records (PTR) were used to develop Boston’s UBEM. GIS shape files define building footprints, volumes, function, and orientation. PTR defined vintage and structure types. The non-geometric properties of the archetypes (reference models), such as thermal properties, glazing ratios, internal loads for equipment, lighting use, HVAC settings and operation schedules were based on data collected through the building segmentation process, existing energy codes, and previous documentation of existing buildings. In total, 19 building operations, five end-uses, and four vintages were developed to represent Boston’s building stock. One thermal zone per floor and single-use buildings were assumed due to simulation times and data availability. Results from the simulation of developed archetypes were compared against measured building energy uses for that building type from Commercial and Residential Building Energy Consumption Surveys (CBECS). The error of the average EUI compared to the CBECS national average was within an error range of 5% to 20%.

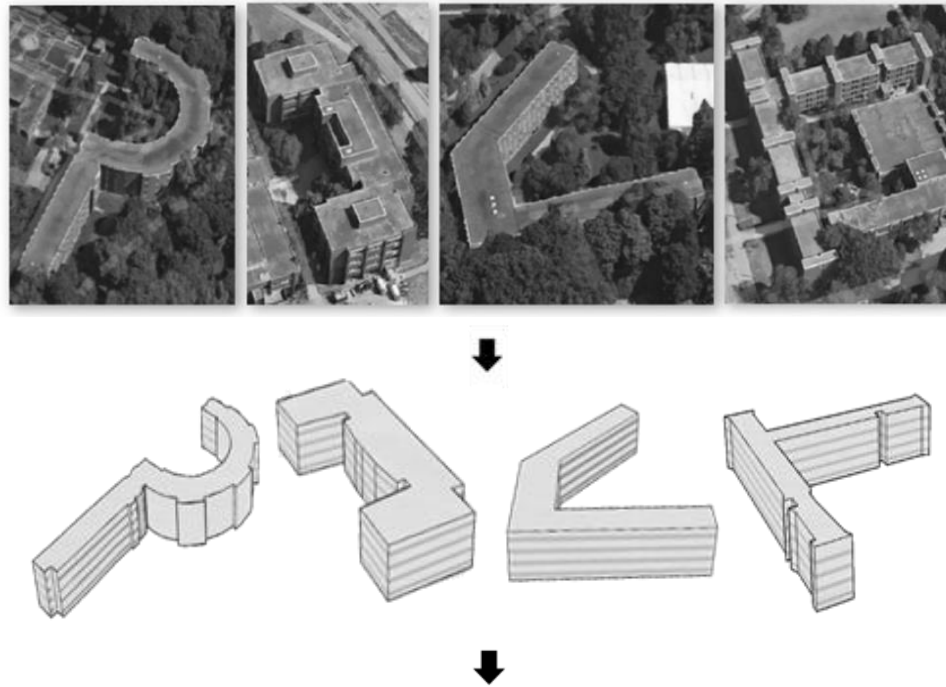
From this review, two distinct bottom-up methods have been identified. The method where one reference model is developed to represent the consumption of all buildings in a sample, and the method, where all buildings in a sample are modeled considering their real form. Although, both methods use reference models to predict consumption, one is more complex as it considers the real geometry and orientation of all buildings in a sample. Both methods have been selected for review to determine if the additional effort in modeling buildings using their real form results in more accurate predictions. Understanding how the methods compare to one another and their differences when different sample sizes are considered will allow to better understand the benefits and limitations of each.

### 3 Methodology

As discussed in the Literature Review, there is no single agreed approach to developing reference energy models for building stock analysis [10]. This section presents the quantitative approach that was used to evaluate the two bottom-up approaches, the *Reference* method and the *Wireframe* method, for exploring energy efficiency solutions at district or regional scales. Though both the *Reference* and *Wireframe* methods consider average characteristics of a building sample alongside U.S. DOE commercial reference model inputs, the *Reference* method (Figure 1) uses a single model and scales its normalized consumption using area factors to predict the aggregate consumption of a sample, while the *Wireframe* method (Figure 2) uses geometric and orientation characteristics of all buildings in a sample to predict individual consumption which is then added to represent the aggregate consumption of the sample.



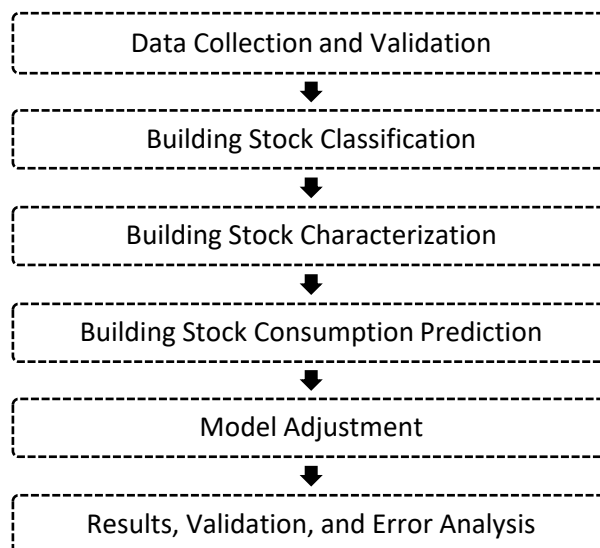
**Figure 1.** This image shows how the *Reference* method predicts aggregate consumption. A simplified energy model is developed to represent a typology of buildings. After simulation, the area normalized consumption of the model is multiplied by measured areas of buildings with same typology to predict the aggregate energy consumption



Est. Student Residence Energy = 1,973 MWh + 1,986 MWh + 2,155 MWh + 1,926 MWh  
 Est. Student Residence Energy = 8,041 MWh/year

**Figure 2.** For the *Wireframe* method, each building in the sample is modeled using its real geometry and orientation. The individual consumption is added to represent the aggregate load of the sample.

Figure 3 presents a flowchart of the approach taken to evaluate the two bottom-up methods using Southern Ontario post-secondary buildings as a case study. A summary of each step follows.



**Figure 3.** Flowchart summary of the development and evaluation of the *Wireframe* and *Reference* models

### 3.1 Data Collection and Validation

Electricity and fuel consumption for 308 post-secondary institutional buildings in climates representative of Toronto (Climate Zone 5) were collected from Ontario MER data and utilized to develop energy benchmarks. These energy benchmarks were developed to validate the collected institutional consumption data – through comparison with results of other benchmarking studies - and to inform consumption differences between university and college buildings. Since erroneous data is found in all data sources, unless proven otherwise, it was important to carefully identify and remove any suspicious entries. Before any detailed analysis was performed, data was checked analytically and visually to remove obvious erroneous data. The identification of outliers was also undertaken; such outliers can exist in datasets due to imprecisions in measurements influenced by instrument sensitivity, human error, or improper judgement of environmental factors that can alter results. The following equations described by Tukey [45] were used to identify energy outliers present in collected building consumption data:

$$IQR = Q_3 - Q_1 \quad (1)$$

$$LAV = Q_1 - 1.5 * IQR \quad (2)$$

$$UAV = Q_3 + 1.5 * IQR \quad (3)$$

Where: IQR is the interquartile range, Q1 is the 25<sup>th</sup> percentile and Q3 is the 75<sup>th</sup> percentile. Only values that were above the LAV value and below the UAV value of a sample were considered. The LAV and UAV set a range of acceptable values according to Tukey's study.

Over 1 million m<sup>2</sup> of college and 2.75 million m<sup>2</sup> of university conditioned floor areas were considered in this study. College and university buildings were originally considered in the same category to replicate the “college/university” benchmark displayed in Energy Star Portfolio Manager 2016 data [24]. College and university institutions were also compared separately to determine if their consumptions differed. To further break down college and university consumption loads, post-secondary buildings were then categorized by their use, including the following: 1) Administrative offices and related facilities, 2) Recreational facilities, 3) Laboratories, and 4) Student residences. The results of this section led to the ideal building operation for comparing the bottom-up methods and their consumption prediction capabilities.



### 3.2 Building Stock Classification

Student residences were identified as a suitable operation to evaluate the bottom-up methods as their EUI were most similar between colleges and universities, while also presenting the lowest errors when compared to Canadian benchmarking studies. Within Southern Ontario, 27 student residence buildings were selected using MER data to predict the consumption of these buildings, a series of reference energy models needed to be developed. Reference model generation consists of two critical steps: classification, or the grouping of buildings with similar properties, and characterization, where a complete set of thermal properties and building systems are defined [46]. To further classify Southern Ontario student residences, their construction period (vintage) and size were considered (Figure 4).



**Figure 4.** Building variables used to classify post-secondary buildings in this study (image from [www.cgtrader.com](http://www.cgtrader.com))

To classify the student residence stock by vintage and size, additional building characteristics had to be collected. These descriptors were obtained from MER data, GIS data, web sources and visual judgment. MER data was used to identify the address, conditioned floor area, and individual consumption of sampled buildings. With reported addresses, GIS data [47, 48, 49, 50], and Daft Logic [51], building height and footprint areas were determined. Campus websites and Toronto Architectural Conservancy data [52] were used to identify the construction period of the residences. Construction periods not available with these sources were defined through visual judgment, as were the number of floors of each building. The three categories used to classify buildings by their size are described in Table 1.

**Table 1.** Description of size categories used to classify Southern Ontario student residences

Size Category Descriptions	
Low-rise	Buildings or houses with 5 floors or less
Mid-rise	Buildings with more than 5 floors and less than 10 floors
High-rise	Buildings with over 10 floors

For consistency with existing DOE reference models for other typologies, three vintage periods were chosen: pre-1980, post-1980 and post-2004. The average age of university buildings in Ontario according to the Council of Ontario Universities (COU) is 42.9 years [53]; although post-2004 buildings were used in the segmentation process, they are considerably less common in the available dataset and were omitted since sample sizes would produce statistically insignificant results. Building vintage characteristics are described in Table 2.

**Table 2.** Description of vintage categories used to classify Southern Ontario student residences

Vintage Category Descriptions	
Pre-1980	Historic masonry buildings Buildings that contained brick masonry Buildings with Brutalist architecture (popular in the 60s and 70s)
Post-1980	Default period for buildings that did not meet the other two building periods
Post-2004 (not used in this study)	Buildings that showed contemporary construction methods ( <i>e.g.</i> high use of IGUs and spandrels); these were less worn down it was visually obvious that these had been recently constructed

When the three size categories were combined with the two used vintage categories, a total of six building classes emerged. Outliers were then identified using equations (1) – (3), and suspicious entries were inspected in greater detail and removed if necessary. Reasoning behind the removal of buildings is explained in Section 0. The median consumption of each category and average building descriptors (building height, number of floors, and conditioned floor area) were then collected from each dataset.

### 3.3 Building Stock Characterization

The characterization of a reference energy model is critical in order to use it to simulate building consumption that accurately represents that commonly seen in buildings of a specific size, operation, and vintage. Once buildings within the dataset were classified by type, the next step was to define a complete set of thermal properties, usage patterns, and building systems for each. All non-geometric building properties required for an energy model can be stored in a characterization

“template”. Characterization templates are beneficial for large scale studies, or when performing multiple simulations on buildings that have similar characteristics as building properties can be quickly assigned to massing models.

To develop characterization templates for classified student residences, their construction assemblies, usage patterns, equipment, and system efficiencies needed to be defined. Such aspects are typically collected through surveys or audits, however, there are currently limited studies available to characterize student residence models in such a way

U.S. DOE reference models were reviewed using four categories described in Table 3. The four categories were selected as these are used in several studies published by the DOE.

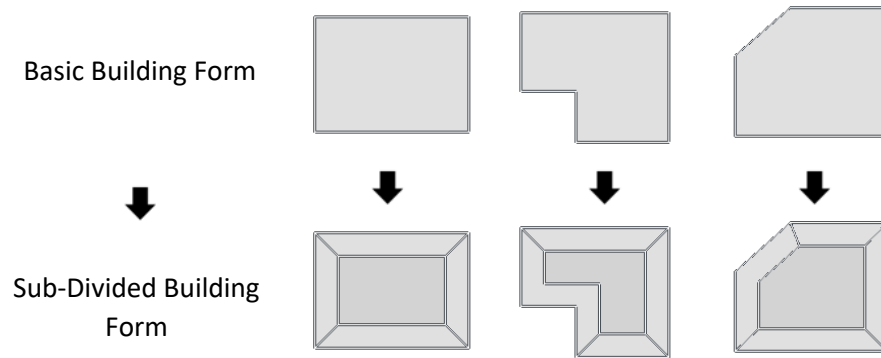
**Table 3.** Building categories used to review commercial reference energy models

Building Category Descriptions	
Form	Conditioned areas, number of floors, aspect ratio, window to wall ratio, shading devices, and floor heights.
Fabric	Air tightness, materials, glazing systems and construction assemblies.
Program	Process loads, ventilation rates, occupancy densities, space activities, domestic hot water demand and operating schedules.
Equipment	Lighting fixtures, HVAC systems, HVAC efficiencies, and control settings.

The floor-to-floor heights, shading devices and aspect ratios of DOE models were reviewed and used to inform geometrical aspects of the student residence models. A floor-to-floor height of 3 meters was set for all student reference models as well as a 30% window to wall ratio. Although using the same floor heights and glazing ratios can reduce the accuracy of consumption predictions due to actual building to building variance, it was determined that it would be best to set the same values for these inputs across all datasets, as to allow for their comparison, regardless of their vintage and size. Materials and characteristics related to the *fabric* of the DOE models informed envelope details of student reference models. To inform space activity breakdowns of the student residence reference models, the floor plans and space activities of DOE models and one Ryerson University residence building were explored. Equipment efficiencies, control settings, and lighting power densities of DOE models were also considered.

The complexity of thermal zoning schemes in energy modeling can increase simulation times, which can be significant when simulating consumption for aggregate scale studies [54]. As stated throughout this thesis, the complexity (level of detail) of an energy model generally depends

on its intended purpose. Including more thermal zones generally improves model accuracy, however, this increases model building time and simulation run time. As student reference models were used to compare two methods for large scale consumption studies, a simplified zoning scheme was employed. Student reference models were auto zoned using the “perimeter/core” method (Figure 5).



**Figure 5.** Zoning example using the perimeter/core method

The summary of characterization templates is described in greater detail in Section 5.2, while the comparison of DOE model inputs and their sources are presented in **Appendix B**.

### 3.4 Building Stock Consumption Prediction

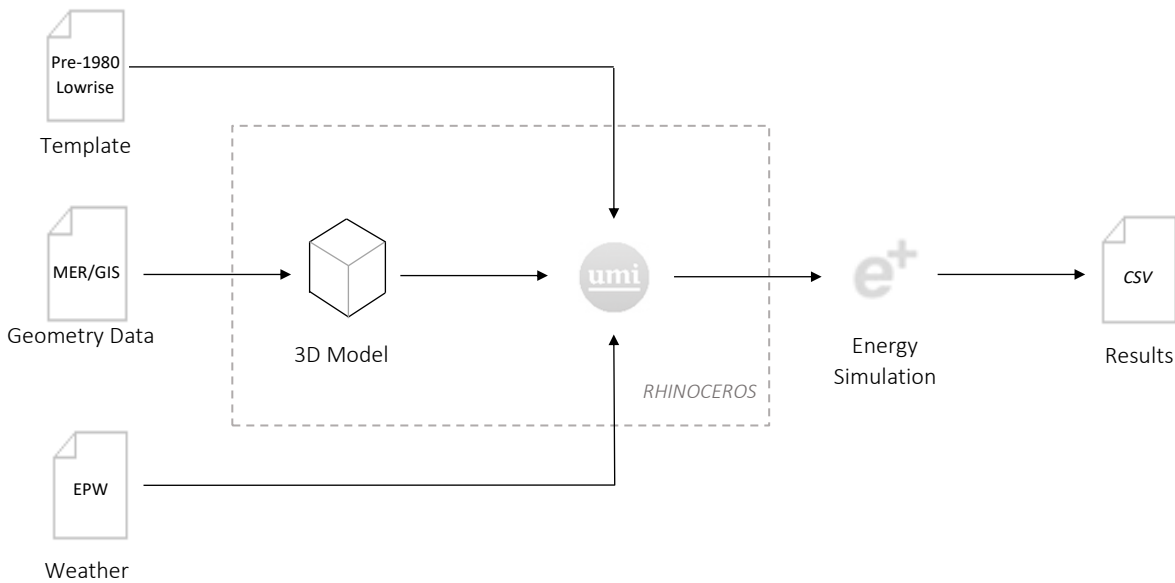
Both approaches predict consumption using EnergyPlus and Urban Modelling Interface (UMI), a Rhinoceros plug-in that serves as an EnergyPlus graphical interface where glazing ratios, floor heights, weather data and other characterization details can be easily applied to an existing geometry. UMI uses the *Shoeboxer* algorithm to create EnergyPlus text files to then be simulated with the software [55]. The Shoeboxer algorithm consists of closed poly-surfaces, so called boundary representations (BREP). Each BREP consists only of spaces of equivalent activity use, *i.e.* a building with laboratory space at the bottom and residence space on top would consist of at least two BREPs. For each activity there should be a zone characterization template that contains all non-geometric building assumptions such as construction assemblies, internal gains, occupancy parameters and HVAC settings and controls. To create a BREP, a building model needs to be created. This is done by drawing a 2D footprint and extruding it to a desired height (Figure 6). When the 3D model is set, the number of floors, glazing ratios, and activities can be assigned.



**Figure 6.** Process used to create 3D building geometry

In addition to building geometry, floor partitions, window-to-wall ratio, construction assemblies, internal gains, conditioning systems, and controls must be defined to run a BEM simulation. These inputs are applied to UMI models using “Unit Properties” and “Zone Templates”. Unit properties contain floor-to-floor heights, perimeter offsets, and window-to-wall ratios. Zone templates contain materials, construction assemblies, internal mass properties, glazing properties, schedules, number of occupants, equipment densities, lighting densities, and control strategies. Each 3D model is assigned to a unit property container and a zone template; however, a second Zone Template can be specified in case the 3D model has a core region that is used for a different purpose to the one used in perimeter regions. The algorithm divides a unit into floors by using a user-defined floor-to-floor height, resulting in unit floors. The algorithm divides the area of a unit floor into core and perimeter regions by offsetting floor edges inwards, this perimeter-offset value is also user-defined. The partition between the perimeter and core zone is modelled as opaque surface, however, glazing can be specified to consider radiative exchange between the two zones. Once these geometric aspects are defined, zone properties such as, materials, construction assemblies, power densities, and occupancy profiles can be applied to the zones. Zones are conditioned with an ideal heating and cooling system by UMI. A weather file is then assigned to the shoebox 3D model which is then converted into an input file for EnergyPlus. As student residences compared in this study are in climates representative of Toronto, a Canadian Weather Year for Energy Calculation (CWEC) file for the city of Toronto was used as the weather file for all simulations. CWEC files contain hourly weather observations to represent an artificial one-year period specifically designed for energy calculations. “The National Energy Code of Canada requires the use of a CWEC file representative of a location when the performance path and customized design calculations are chosen as the means of a building energy consumption compliance” [56].

Figure 7 shows the approach used to develop the energy demand of student residences using Rhinoceros, UMI, and EnergyPlus. In summary, geometry data was collected and used to develop a 3D Model. Characterization details of the desired typology and weather data were applied to the 3D Model using UMI. UMI then converts the 3D model into an EnergyPlus file and simulated using the software.

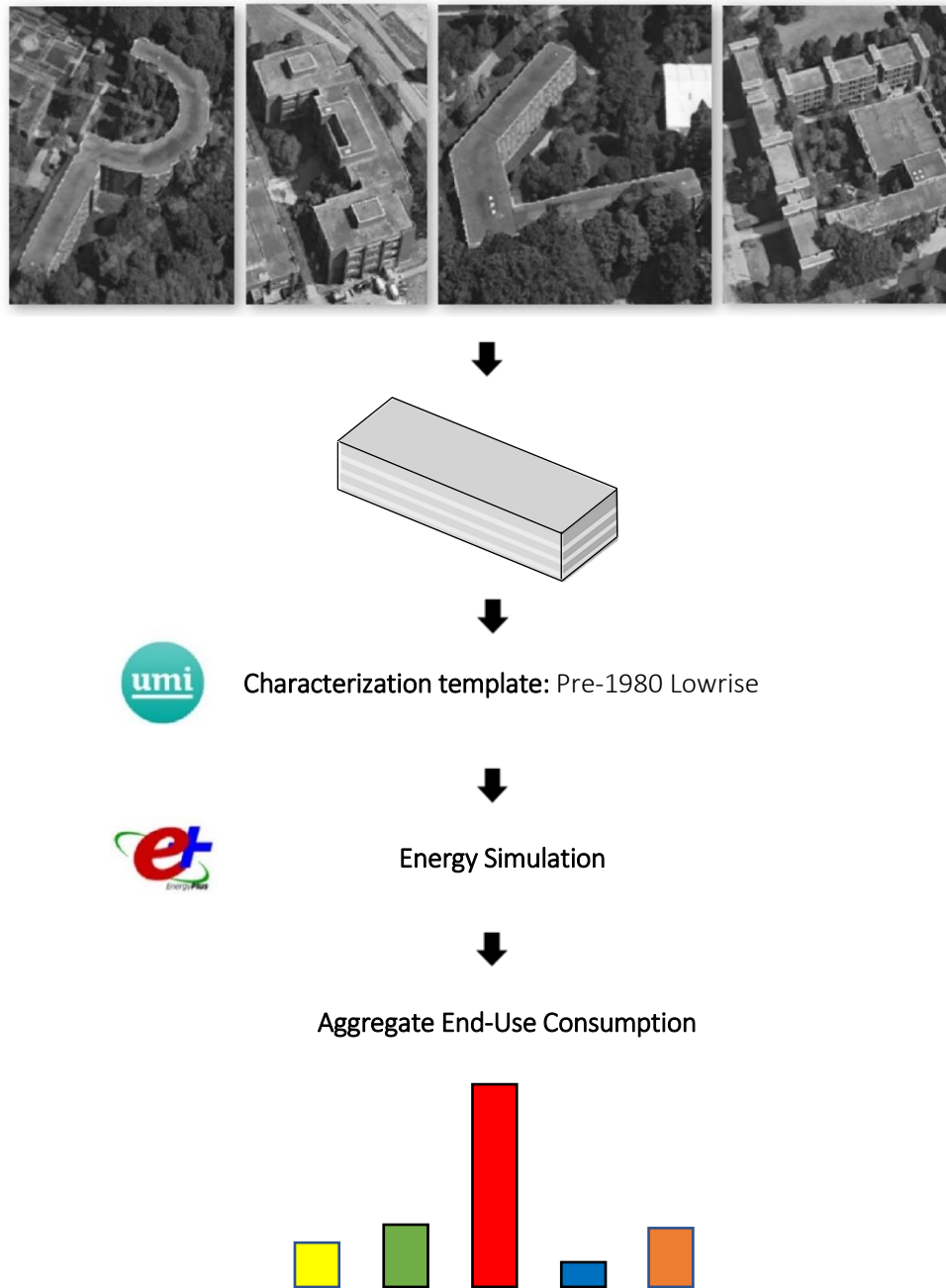


**Figure 7.** Approach used to develop the energy demand of student residence reference models

### 3.4.1 Reference Method Consumption Prediction

One *Reference* model was used to predict the consumption of each dataset of buildings as illustrated in Figure 8. Collected average descriptors (*i.e.* height, area) of each set were used to create a simplified model using Rhinoceros and UMI as the modeling interfaces. The model has a rectangular geometry and an aspect ratio based on the DOE reference model review. The *Reference* model was simulated facing both east-west and north-south to consider the impact that orientation has on building consumption. The glazing ratio was set to 30% on all facades and a floor-to-floor height of 3m was assumed. Floors of the models were subdivided into five zones, four perimeter zones and one core zone. A 3m offset was applied to define the perimeter zone. These values were used in all *Reference* models to allow the comparison of results across datasets for simplicity reasons, all zones were defined by the same activity template, which was defined to represent multiple activities typically seen in student residences. A Toronto CWEC weather file and a characterization template (created through the review of DOE models) were applied to the

*Reference* model to predict its consumption. Results predicted with each orientation were averaged and multiplied by measured conditioned floor areas to determine the aggregate heating, electricity, and total consumption of a dataset.

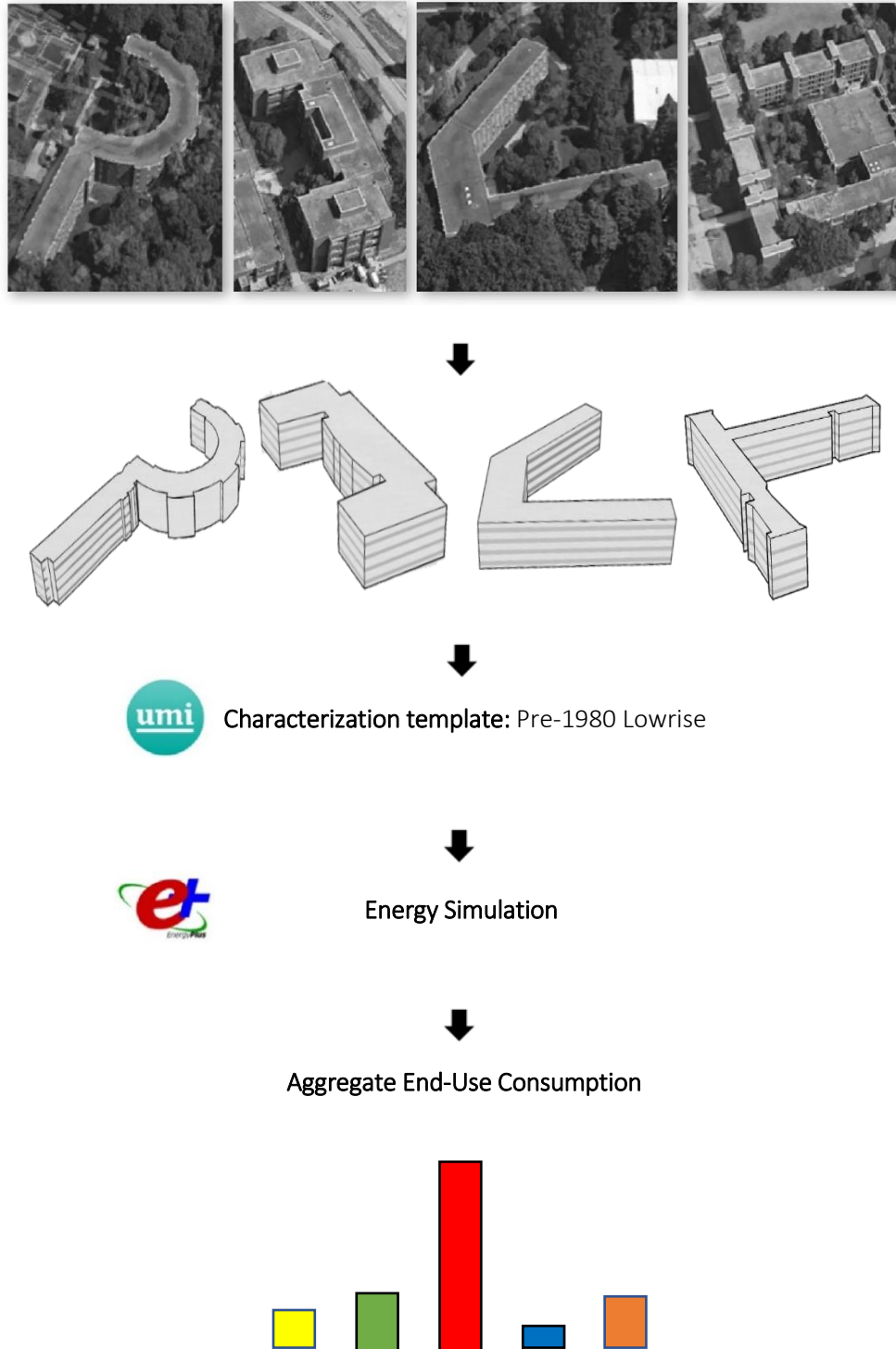


**Figure 8.** Steps to predict consumption using the Reference method: 1) Collection of average building characteristics from a dataset of buildings, 2) Development of Reference model geometry (two orientations), 3) Allocation of weather file and characterization template, 4) Reference model simulation using Energy Plus, and 5) Area normalized consumption predicted from both models are averaged out and multiplied by the total conditioned floor area of the set of buildings.

### 3.4.2 Wireframe Method Consumption Prediction

A *Wireframe* model was built for each building part of a dataset as illustrated in Figure 9. GIS data and Daft Logic were used to obtain building footprints and heights. Footprints were imported to Rhinoceros and extruded to meet a reported height. Once 3D geometries were finalized, UMI was used to apply a glazing ratio of 30% on all facades and a 3m floor-to-floor height. A Toronto CWEC weather file and a characterization template were applied to each of the *Wireframe* models. Floors of the models were subdivided into five zones, four perimeter zones and one core zone. A 3m offset was applied to move the floor edges of the perimeter zone inwards. For simplicity reasons, all zones were defined by the same activity template, which was defined to represent multiple activities typically seen in student residences. *Wireframe* models were simulated using EnergyPlus to determine their heating, electricity, and total energy. Consumption results are added to determine the aggregate heating, electricity and total consumption of a dataset.

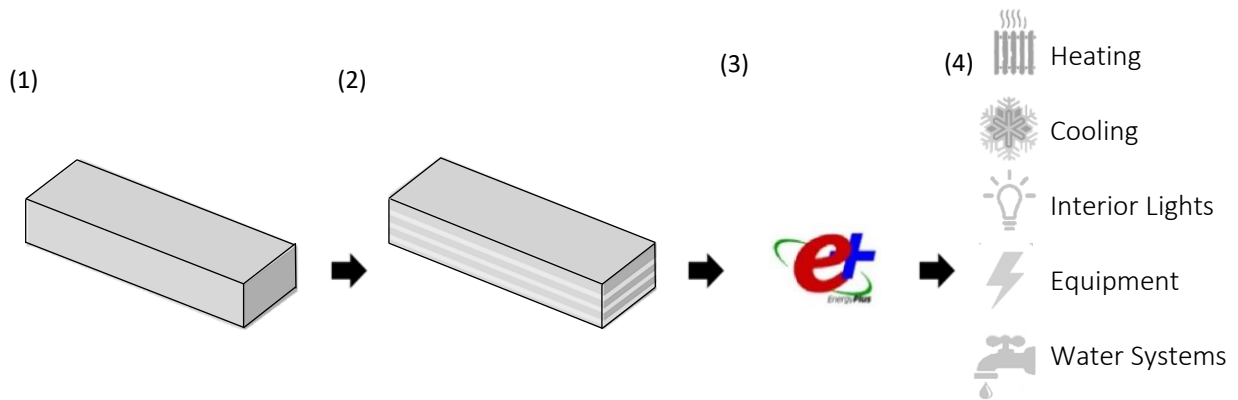




**Figure 9** Steps to predict consumption using the Wireframe method: 1) Collection of average building characteristics from a dataset of buildings, 2) Development of Wireframe model geometry, 3) Allocation of weather file and characterization template, 4) Simulation using Energy Plus, and 5) Individual building consumption are aggregated to represent the total consumption of the dataset of buildings.

### 3.5 Model Tuning

Once characterization details were assigned to a *Reference* method model, their consumption was predicted using EnergyPlus. Each *Reference* model predicted five annual end-uses: heating, cooling, interior lighting, interior equipment, and water systems (Figure 10). End-use predictions were later normalized using the conditioned floor area of the *Reference* model used to produce them.



**Figure 10.** This image describes the process of predicting the end-use consumption of a Reference model: (1) A Rhinoceros 3D model is created using geometrical characteristics of the building stock, (2) Characterization templates and weather data are applied to the 3D model using UMI, (3) The *Reference* model is simulated using Energy Plus, and (4) The end-use consumption of the model is then determined predicted.

Because two existing DOE models were merged to best match the desired building typology, student residence models were tuned to ensure that the results were consistent with the DOE models (either matching or falling between them) rather than differing significantly from them. If the predicted consumption of a student residence model was significantly off, their characterization template was adjusted, as will be discussed in detail in Section 6. Once characterization templates were adjusted, they were applied using the *Wireframe* and *Reference* methods to predict the consumption of student residences.

### 3.6 Institutional Residence Building Stock Validation and Error Analysis

The predicted aggregate annual heating, electricity and total consumption derived from both methods was compared to their equivalent consumption reported in the MER to validate the results of each method. To test the hypothesis that the *Wireframe* method would provide better prediction accuracies than the *Reference* method, an error analysis study was undertaken. Percentage Error (E) represents the capabilities of the methods to predict aggregate load consumption. This equation is very useful to determine the precision of calculations.

$$(E) = \left( \frac{(\sum loads_{Predicted} - \sum loads_{Measured})}{\sum loads_{Measured}} \right) \quad (4)$$

Root Mean Square Error (RMSE) represents the sample standard deviation of the discrepancies between predicted and measured values.

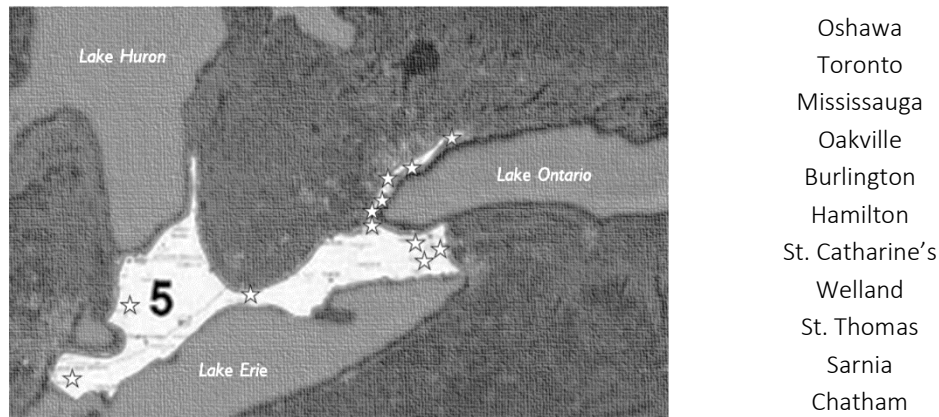
$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n \left( \frac{x_{Predicted} - x_{Measured}}{x_{Measured}} \right)^2} \quad (5)$$

Together, the Percentage Error and RMSE equations allow the model accuracies to be evaluated at both aggregate and individual building scales. In addition to the bottom-up method comparison and accuracy evaluation, a study to determine their capabilities with varying sample sizes was explored. For this study, the final building results were imported into a database and randomly sampled without replacement to generate building subsets of varying sizes (n=3,5,7,9,11,13,15,17 and 19) with replacement between subset generation. The predicted annual total energy of each building was then totaled for each subset and compared with actual totals for the same buildings. The average error rate was then plotted against sample size for each method.

*The methodology presented here was used to determine if the inclusion of real geometry and orientation of buildings can have a significant effect on the outcomes of energy prediction for conservation strategy testing at regional scales.*

## 4 Data Collection and Validation

In 2009, Ontario's Ministry of Energy implemented Regulation 397/11 [16] under the Green Energy Act. This regulation requires municipalities, post-secondary, and healthcare operations to annually report their energy consumption, carbon emissions, building operations, and some building characteristics that influence a building's energy consumption. Data collected from these reports is referred to as Mandatory Energy Report (MER) data throughout this thesis. As noted above, MER data collected by the MOE of Ontario was used to determine the energy performance of college and university buildings within climate zones similar to that of Toronto. Figure 11 shows Southern Ontario's climate zone delimitation as described by the NECB (2011) [57]. The stars displayed on Figure 11 represent cities which contain buildings considered in this study.

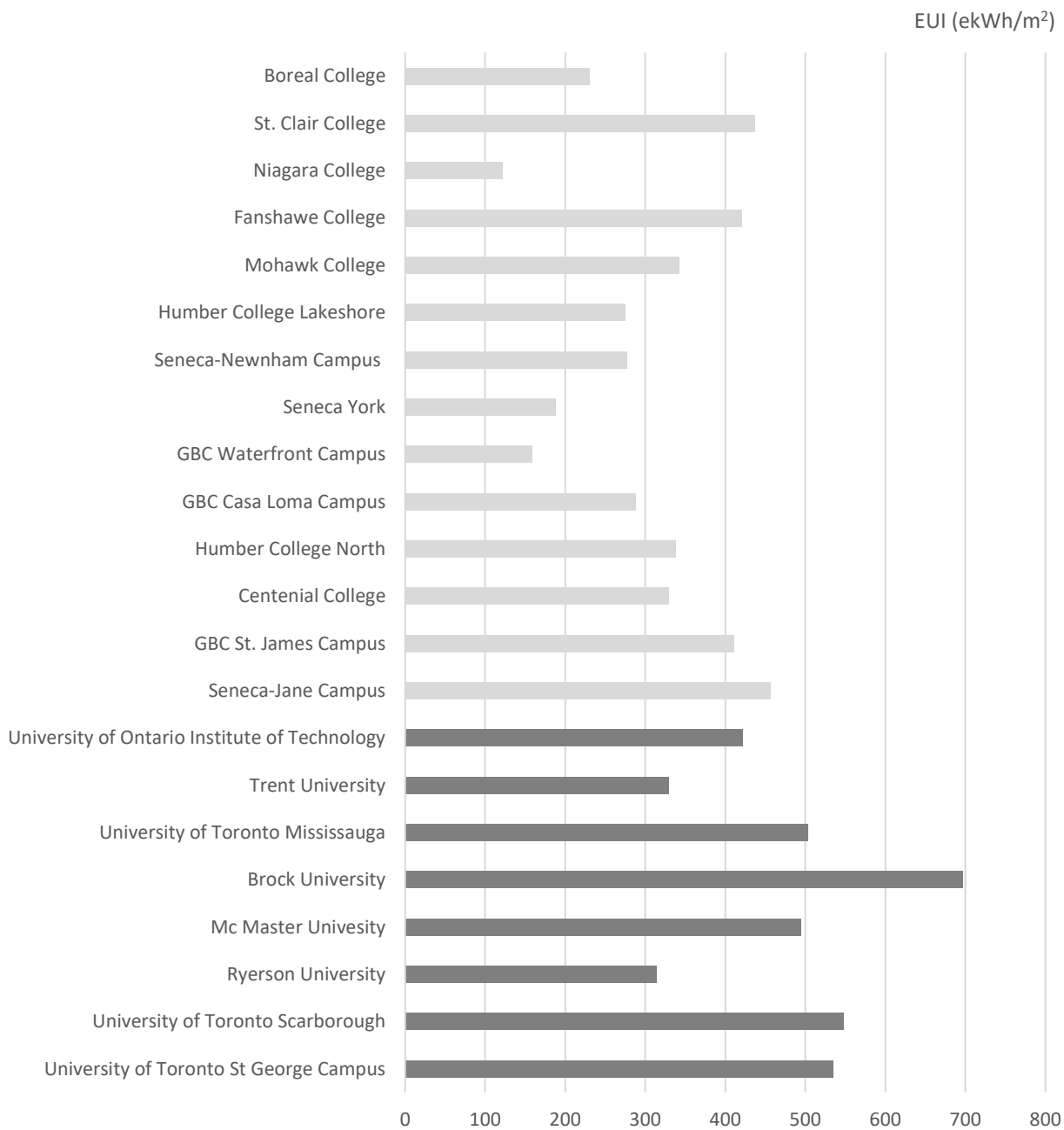


**Figure 11.** Climate Zone 5 (NECB 2011) and cities where MER institutional data was collected

This climate classification resulted in a sample size of 8 universities and 14 colleges, representing 308 post-secondary buildings. The selection of only those buildings that met this criteria aids in the development of more granular benchmarks. Energy benchmarks developed from MER data were then compared against Canadian benchmarking studies to validate the data from the reports - this was necessary since MER data is not validated by the MOE. Those post-secondary building operations which compare favorably to Canadian benchmarking studies are considered “validated” and their data can be used to develop the reference energy models of Ontario's institutional building stock. Developed benchmarks were also used to inform consumption differences between university and college building operation. The results will help to identify building operations suitable for a comparison of the bottom-up methods. The findings of this investigation are summarized in this section.

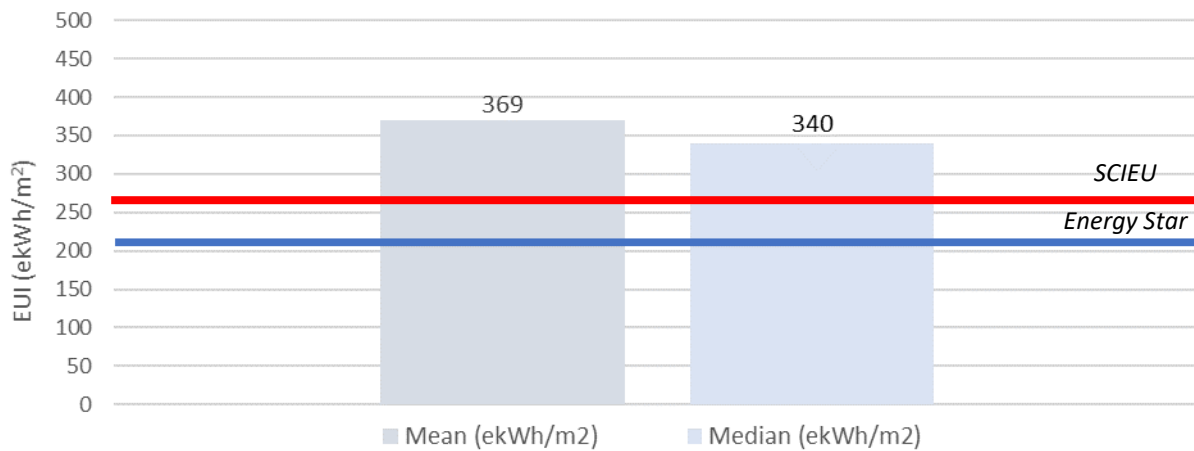
## 4.1 Data Validation for Colleges and Universities

To validate the consumption reported for colleges and universities, their energy use intensity (EUI; measured  $\text{ekWh/m}^2$ ) and area ( $\text{m}^2$ ) were collected. Figure 12 presents college and university EUIs collected from Southern Ontario MER data.



**Figure 12.** EUI of selected college and university institutions

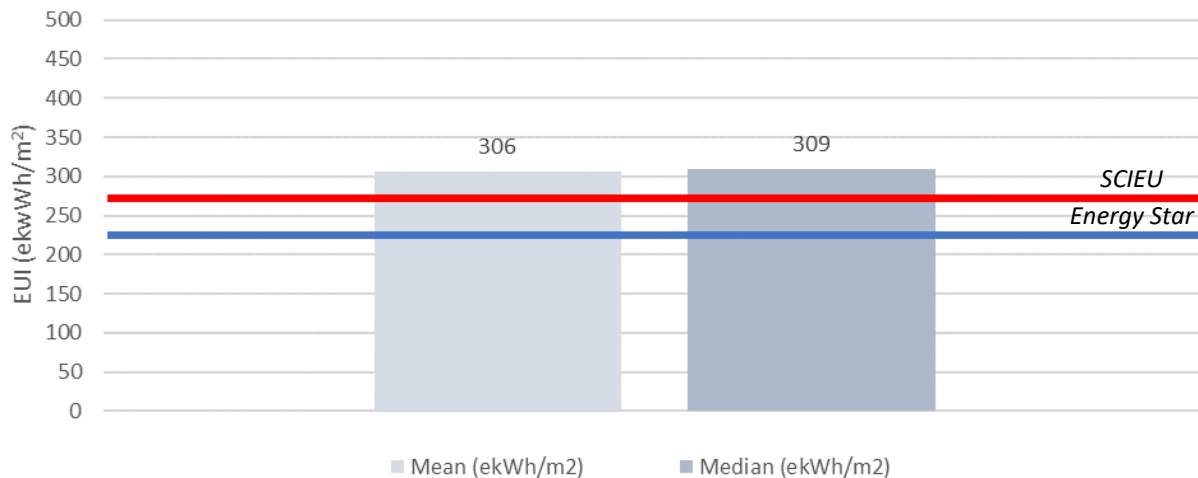
First, college and university buildings were considered in the same category to replicate the “college/university” benchmark displayed in Energy Star Portfolio Manager 2016 data [24]. Equations (1) - (3) were applied to the EUI of the 22 post-secondary institutions displayed in Figure 12. No energy outliers were identified in the sample. The mean and median EUI derived from the MER college/university category are compared to the *college/university* EUI benchmark defined in *Energy Star* 2016 data, and the EUI of the *other* category defined in the *Survey of Commercial and Institutional Energy Use: Buildings 2009* [22] in Figure 13.



**Figure 13.** Mean and median EUI derived from the MER college/university category compared to the 212 ekWh/m<sup>2</sup> (Energy Star) and the 264 ekWh/m<sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies

As stated in the Literature Review, universities and colleges in the SCIEU survey are grouped under the “other” category which includes entertainment, leisure, and shopping centres. This variation in building operation affects the accuracy of the benchmark as a building’s function is a primary driver of its energy consumption. The “other” benchmark presented in the SCIEU survey has a median EUI for Ontario’s Great Lakes region of 264 ekWh/m<sup>2</sup> [22]. The “college/university” benchmark presented in Energy Star’s Portfolio Manager Technical Reference document, which was derived from national surveys, shows a median value of 212 ekWh/m<sup>2</sup> [58]. The comparison of these values suggests that the developed median of 340ekWh/m<sup>2</sup> for Southern Ontario’s college/university category exceeds the EUI found in Canadian benchmarking studies. It was noted that the mean and median values produced by MER data differ by 9%, suggesting variance across the sample, illustrating that colleges and universities should be considered separately.

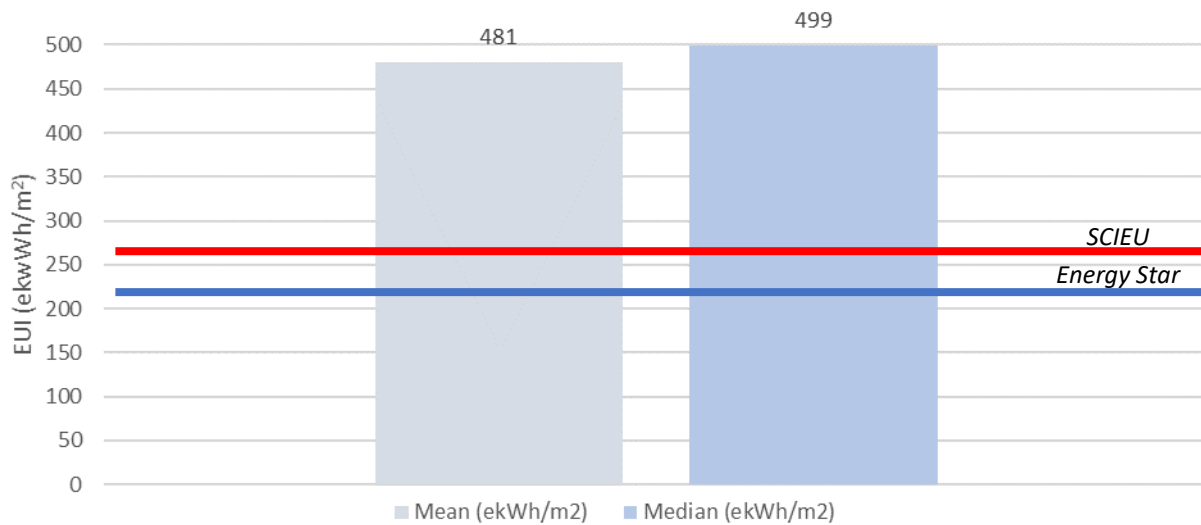
Southern Ontario colleges were analyzed first, covering over 1.06 million m<sup>2</sup> of conditioned floor area. Equations (1) - (3) were applied to EUIs of the 14 colleges displayed in Figure 12. No energy outliers were identified in the college category. The mean and median EUI derived from the college category are compared to Canadian benchmarking studies in Figure 14.



**Figure 14.** Mean and median EUI derived from the college sample compared to the 212 ekWh/m<sup>2</sup> (Energy Star) and the 264 ekWh/m<sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies

Figure 14 shows that Canadian benchmarking studies exceed the average of the sample of buildings selected, however the difference between the developed EUI and the benchmark studies decreased. In addition, a 1% difference in variation was noted between the mean and median, which suggests that considering colleges exclusively results in a more uniform sample.

Southern Ontario universities were then analyzed, covering over 2.75 million m<sup>2</sup> of conditioned floor area. Equations (1) - (3) were applied to EUIs of the eight universities displayed in Figure 12. No energy outliers were identified in the university sample. The mean and median EUI derived from sampled Ontario universities is compared to the EUIs defined in North American benchmarking studies in Figure 15.



**Figure 15.** Mean and median EUI derived from the MER university sample compared to the 212 ekWh/m<sup>2</sup> (Energy Star) and the 264 ekWh/m<sup>2</sup> (SCIEU) displayed in Canadian benchmarking studies

Figure 15 shows that Canadian benchmarking studies exceed the average of the sample of buildings selected, however the difference between the developed EUI and the benchmark studies increased. In addition, a 1% difference in variation was noted between the mean and median, which suggests that considering university exclusively results in a more uniform sample.

These results propose a measurement error in MER data, though it is important to note the limitations of the Canadian benchmarking studies. The Energy Star benchmark represents a national consumption average of colleges and universities and the SCIEU benchmark represents “other” buildings in climates similar to that of the Great Lakes. Therefore, it is challenging to determine which benchmarking survey is more accurate as neither study presents the required granularity. Additionally, the results of these studies may be skewed by the total floor area of the college and university buildings considered. It is possible that the SCIEU survey included more college conditioned floor area, while the Energy Star survey included more university conditioned floor area. Although both studies include the total conditioned floor areas considered in benchmark development, neither disclose the percentage attributed specifically to university, college or other operation buildings. Without this, it is challenging to present a definitive answer on which benchmark survey is more appropriate to validate MER data. However, when college and university institutions were considered as separate samples, the difference between their mean and median decreased when compared to the initial college/university sample. This suggests that



considering college and university buildings separately does produce less scattered samples. The question that now arises is: *Which college and university building operations differ the least in consumption?* The answer will identify the building operation most ideal for comparing the bottom-up methods discussed later in this thesis. The building operations with the least EUI variation between colleges and universities will produce larger samples for the comparison. Additionally, if a sample compares well with existing benchmarks, it is assumed to be the best option for method comparison. This approach was necessary due to the limitations in considering only buildings part of the MER data.

## **4.2 Data Validation for College and University Building Operations**

MOE requires universities and colleges to report their energy consumption based on the space's designated use using the following categories: (1) Administrative offices and related facilities, (2) Classrooms and related facilities, (3) Laboratories, (4) Student residences, (5) Recreational facilities, (6) Parking garages, and (7) Other. The reported consumption of these operations was reviewed in greater detail with the exception of Classrooms, Other and Parking categories due to their complexity and/or variability. The intention of this review is to analyze and validate in greater detail MER data by developing local energy benchmarks, comparing them to North American benchmarks, and determining the deviation between building operations at colleges and universities. The results of this review were used to validate the MER data and identify potential benchmarks and/or reference models applicable to both college and university buildings.

### **4.2.1 Building Operation Data Cleaning**

Under MER regulations, building owners must submit an operation type based on the primary function given to a space. Many institutional buildings serve multiple operations per building, and this is clearly shown in MER data as some institutions submit multiple operations under one building address, as illustrated in Table 4. Although in the MER dataset buildings are presented with different operations and areas under the same location, the reported EUI is based on the total consumption of the building and not on a space-by-space basis. Knowing the multiple uses or operations that are given to a building serves a greater understanding of the variances in EUI. For example, Progress Residence has space allocated both for residences and for laboratories

while also boasting the largest EUI in the *College Residence* data set. In this case, the energy required to power laboratory equipment is more than likely what is causing the variance in EUI when compared to the EUI reported under other Residence buildings.

**Table 4.** Buildings reported under the same location for college residences

Building Name	Operation Type	Address	Area (m <sup>2</sup> )	EUI (kWh/m <sup>2</sup> )	Area (%)
Lambton Inn	Residence	1485 London Rd.	5880	330	76
Lambton Inn	Office	1485 London Rd.	1877	330	24
Progress Residence	Residence	940 Progress Ave.	10602	418	70
Progress Residence	Laboratory	940 Progress Ave.	4520	418	30
Newnham Residence	Residence	1760 Finch Ave.	29990	241	83
Newnham Residence	Office	1760 Finch Ave.	5991	241	17

Information regarding the space type is useful, however EUIs on a space-by-space basis would be necessary for a more accurate analysis. Because considering each operation as an individual building creates duplicate buildings, buildings that reported multiple operations under one location are joined and classified under the main use that the building serves Table 5. This “main use” assumption allows buildings to be represented by their total area rather than segments and permits comparison on a building-by-building basis.

**Table 5.** Buildings with multiple operations after relevant data has been joined to form a building

Building Name	Operation Type	Address	Area (m <sup>2</sup> )	EUI (kWh/m <sup>2</sup> )	Area (%)
Lambton Inn	Residence	1485 London Rd.	7757	330	100
Progress Residence	Residence	940 Progress Ave.	15122	418	100
Newnham Residence	Residence	1760 Finch Ave.	35982	241	100

#### 4.2.2 Administrative Office Buildings – College Sample

Administrative office buildings of eight college campuses were considered to develop the Administrative Office university benchmark, resulting an initial sample size of 36 buildings. The average EUI, total energy consumption, number of buildings (n), and area of considered administrative office buildings for college campuses are presented in Table 6. The median EUI derived from the initial sample (n=36) can be seen in Table 7.

**Table 6.** Initial sample of Administrative Office buildings considered for benchmarking study

Administrative Offices - Colleges						
College	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca	York	2	2318465	12642	183	17
Seneca	Newnham	11	8703744	31820	274	25
Seneca	Jane	1	179584	393	453	42
Centennial	Scarborough	10	9567871	39711	241	22
St. Clair	Windsor	1	201278	755	266	25
Lambton	Sarnia	6	7448914	50822	147	14
Niagara	Welland	4	14096310	115371	122	11
Sheridan	Trafalgar	1	1037231	2682	387	36

**Table 7.** Administrative Office buildings results before outlier removal

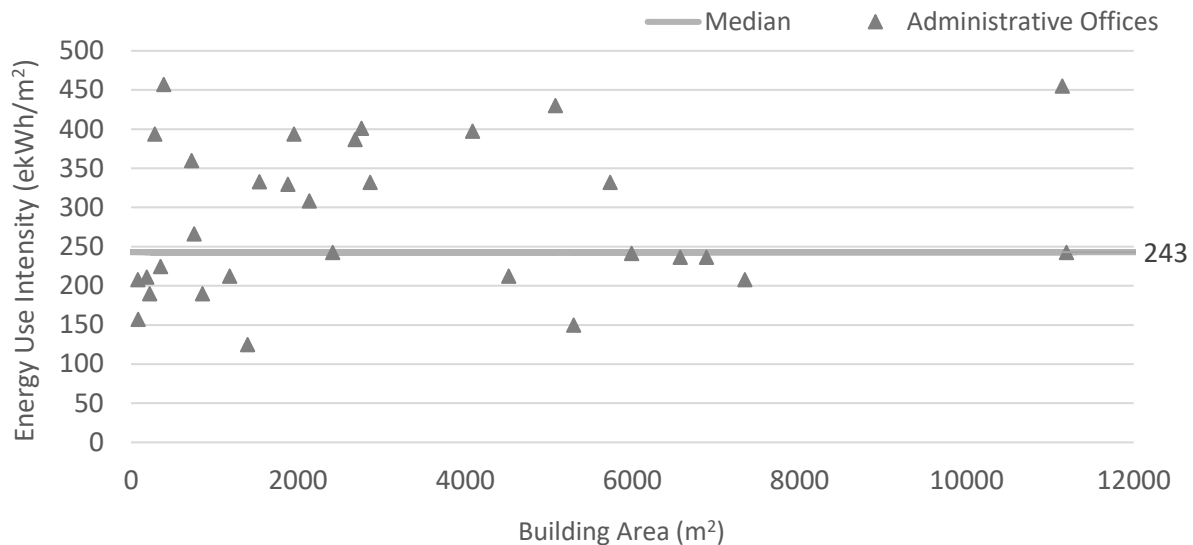
Administrative Offices EUI (ekWh/m <sup>2</sup> ) - Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
210	320	255	394	183	-65	669	183	72%

As seen in Table 7 the initial sample of 36 buildings showed a 25% difference between its mean and median EUI and a sample standard deviation (*s*) of 72%. These findings suggest significant variation across the sample. Three buildings were then identified as outliers using Equations (1) - (3) and two buildings through data screening. Buildings removed through data screening were identified as erroneous entries as their area was suspiciously high (8-10 times larger than that of the average). Identified outliers were removed resulting in a new sample size of 31 buildings. The difference between the developed mean and median EUI decreased by 11% and the standard deviation by 33%, compared to those developed before outlier removal. The results of the Administrative Office college benchmark after the removal of outliers can be seen in Table 8.

**Table 8.** Administrative Office buildings after outliers have been removed

Administrative Offices EUI (ekWh/m <sup>2</sup> ) - After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
212	286	243	373	162	-31	616	96	39%

The EUI and area of each administrative building considered in the development of the Administrative Office college benchmark can be seen in Figure 16. The horizontal line represents the developed 243 kWh/m<sup>2</sup> median after outliers were removed.



**Figure 16.** College Administrative Office buildings considered to develop the sample's EUI

#### 4.2.3 Administrative Office Buildings – University Sample

Administrative office buildings of three university campus were considered to develop the Administrative Office university benchmark, totaling an initial sample size of 33 reported buildings. The average EUI, total energy consumption, number of buildings (n), and area of the studied administrative office buildings per campus are presented in Table 9. The median EUI derived from this initial can be seen in Table 10.

**Table 9.** Initial sample of University Administrative Office buildings considered for benchmarking study

Administrative Offices - University						
University	Campus	n	Σ (kWh)	ΣArea (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Ontario	Oshawa	5	4274590	18691	229	21
York	Toronto	26	95160681	19425	490	45
Brock	St. Catharines	2	45944	870	53	5

**Table 10.** University Administrative Office buildings results before outlier removal

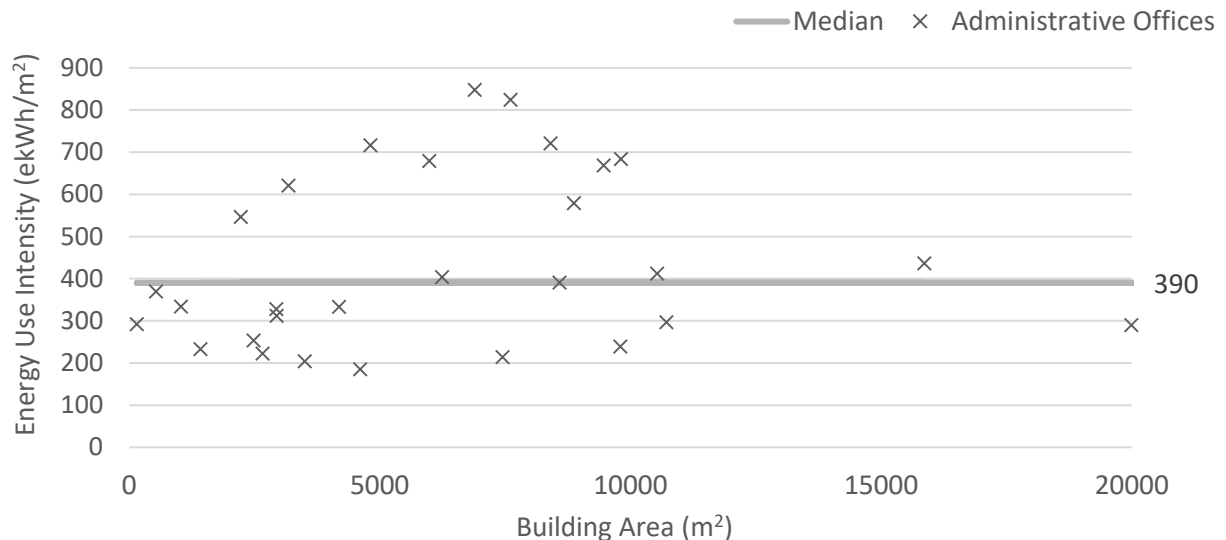
Administrative Offices EUI (ekWh/m <sup>2</sup> ) - Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
253	435	369	620	367	-298	1171	246	67%

As seen in Table 10, the initial sample of 33 buildings showed an 18% difference between its mean and median EUI and a standard deviation of 67%. One building was identified as an outlier using Equations (1) - (3) and two buildings were identified as outliers through screening process. The two buildings identified through the screening process are part of Brock University; while Equations (1) - (4) did not identify these buildings as outliers, they were removed due to a suspiciously low reported consumption (11-25% of reported values for other institutions). Outliers were identified and removed, resulting in a new sample size of 30 university buildings. After this removal, the difference between the developed mean and median EUI decreased by 3% and standard deviation by 8%. The results of the Administrative Office university benchmark free of outliers can be seen in Table 11.

**Table 11.** University Administrative Office buildings after outliers have been removed

Administrative Offices EUI (ekWh/m <sup>2</sup> ) - After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
290	438	380	610	320	-190	1090	201	59%

The EUI and area of each administrative building considered in the development of the Administrative Office university benchmark can be seen in Figure 17.



**Figure 17.** University Administrative Office buildings considered in the developed benchmark

#### 4.2.4 Administrative Office Buildings – College and University Sample

Administrative office buildings at three universities and eight colleges (n=79 buildings) were considered to develop the Administrative Office college & university benchmark. The average EUI, total energy consumption, number of buildings, and area of the studied administrative office buildings per university and college campus are presented in Table 12. The median EUI derived from the initial sample can be seen in Table 13.

**Table 12.** Initial sample of university and college Administrative Office buildings considered for benchmarking study

Administrative Offices – Colleges and Universities					
Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca - York	2	2,318,465	12,642	183	17
Seneca - Newnham	11	8,703,744	31,820	274	25
Seneca - Jane	1	179,584	393	453	42
Centennial - Scarborough	10	9,567,871	39,711	241	22
St. Clair - Windsor	1	201,278	755	266	25
Lambton - Sarnia	6	7,448,914	50,822	147	14
Niagara - Welland	4	14,096,310	115,371	122	11
Sheridan - Trafalgar	1	1,037,231	2,682	387	36
University of Ontario - Oshawa	5	4,274,590	18,691	229	21
York University - Toronto	26	9,516,0681	19,425	490	45
Brock University - St. Catharines	2	45,944	870	53	5

**Table 13.** College and university Administrative Office buildings results before outliers are removed

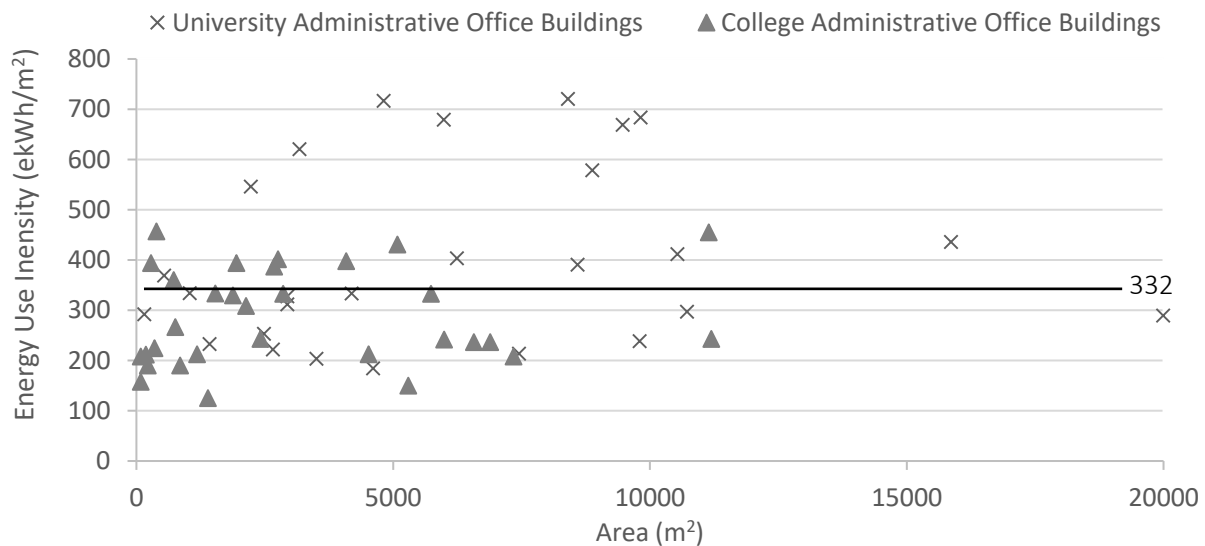
Administrative Offices EUI (ekWh/m <sup>2</sup> ) - Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
237	386	333	456	219	-90	784	185	56%

As seen in Table 13, the initial sample of 79 buildings showed a 15% difference between its mean and median EUI and a standard deviation of 56%. Four buildings were identified as energy outliers using Tukey's screening method. Identified outliers (4 total) were removed and resulted in a new sample size of 75 buildings. Once outliers were removed from the university sample, the difference between the developed mean and median EUI decreased by 6% and standard deviation by 7%. The revised results of the Administrative Office college and university benchmarking can be seen in Table 14.

**Table 14.** College and university Administrative Office buildings after outliers have been removed

Administrative Offices EUI (ekWh/m <sup>2</sup> ) - After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
237	365	332	433	196	-58	728	161	49%

The EUI and area of each administrative building considered in the development of the Administrative Office college and university benchmark can be seen in Figure 18. The horizontal line represents the developed 332 kWh/m<sup>2</sup> median after outliers were removed.

**Figure 18** College and university Administrative Office buildings considered in the developed benchmark

#### 4.2.5 College and University Benchmarking by Building Operation

Benchmarks for other building operations, such as residences, laboratories, and recreational facilities were subjected to the same analysis; the results are presented below in Figure 19. A summary of each analyzed building operation can be found in **Appendix A**.

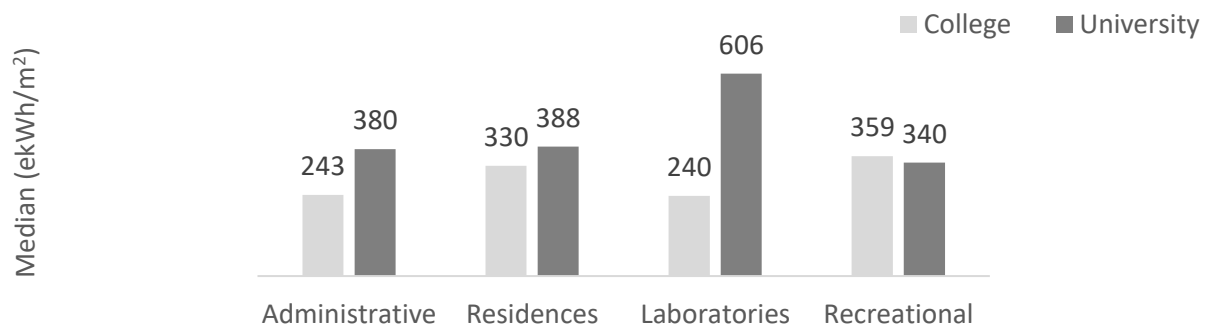
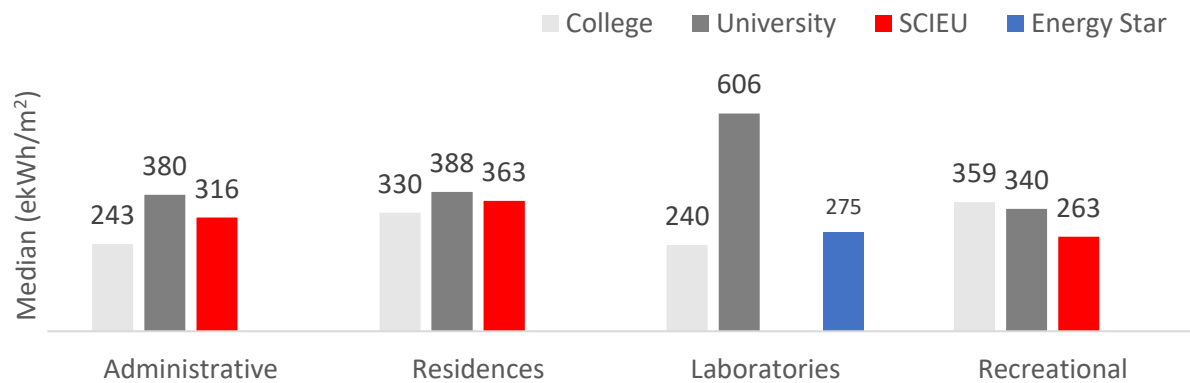
**Figure 19.** Developed Energy Benchmarks for College and University building operations

Figure 20 presents the comparison of developed MER benchmarks to the Energy Star Portfolio Manager benchmark for Canadian Laboratories and SCIEU benchmarks for Great Lakes offices, lodgings and recreational buildings.



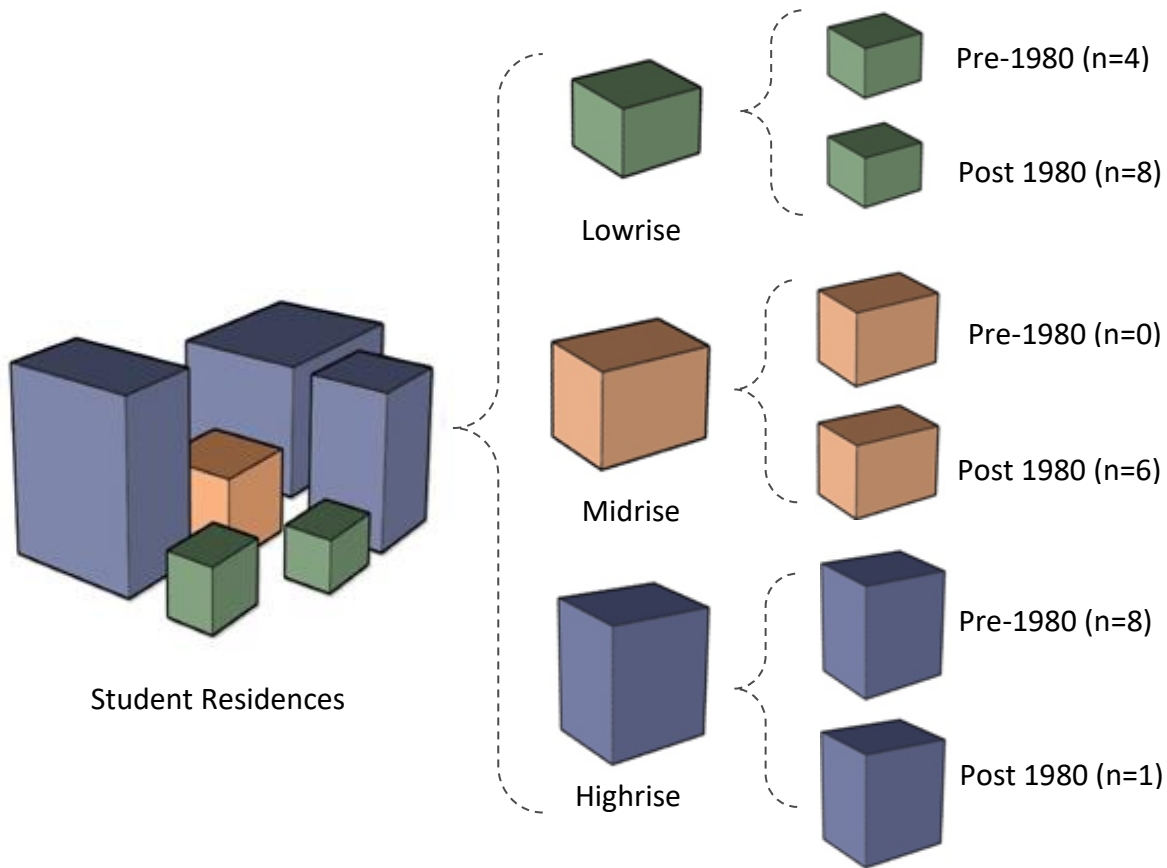
**Figure 20.** Developed MER Benchmarks of Administrative, Residence, and Recreational facilities are compared to SCIEU Energy Star Portfolio Manager Laboratory benchmark is compared to MER laboratories

As seen in Figure 20, student residences and recreational facilities vary the least in EUI between colleges and universities and can be represented with a single college/university benchmark, while post-secondary laboratories would require different benchmarks or reference models to represent each of colleges and universities. Additionally, SCIEU benchmarks were most similar to those developed for residence and administrative office operations. Because a reasonably consistent dataset was required to test the *Wireframe* and *Reference* methods to compare their results, student residences were selected for investigation.



## 5 Building Classification and Characterization

In order to compare the *Wireframe* and *Reference* methods, it was necessary to develop a consistent set of template inputs (i.e. a preliminary reference model) to simulate those buildings whose reported data could be used for model validation and error analysis. Based on the investigation discussed in Section 4, student residences were the simplest dataset to consider. These buildings considered are easily categorized by size (Lowrise, Midrise, Highrise) and vintage (pre-1980 and post-1980), resulting in six building categories (Figure 21). These classes are consistent with the approach used in [26, 27, 28, 29] and are assumed to capture major variations across student residence buildings in Southern Ontario and used as the basis for energy predictions and formed the set of reference models necessary for this analysis.



**Figure 21.** Student residence segmentation using building size and vintage as variables. The number of buildings in the master dataset within each category are indicated in parentheses.

## 5.1 Cleaning of Data Sets

To ensure that energy simulation results would not be skewed by the presence of outliers, Tukey's equations, as described in Section 3.1, were used to identify and remove atypical buildings from each category. These buildings are described below to provide insight on the rational for the exclusion of each.

**Post-1980 Lowrise category:** Four student residences were removed from the original post-1980 Lowrise dataset. The *Lambton Inn Residence* was eliminated because it was not purely a residence, containing significant areas for other uses (classrooms, administrative, *etc.*), which cannot be accurately represented with a student residence characterization template. *Quarryview Residence* was first identified as an energy outlier using Tukey's equations (Eq. 1-3) due to its EUI being suspiciously low. After the building was inspected, it was determined that it should be removed as it was the only building that looked like a townhouse complex in the dataset (Figure 22) *Passy Gardens* was removed as this residence is a complex that contains nine buildings and is thus inconsistent with the defined typology. Finally, *Calumet Residence* was removed as its area is much lower ( $5\,271\text{ m}^2$ ) than the rest of the residences part of this sample ( $7\,218\text{ m}^2$ ,  $9\,290\text{ m}^2$ ,  $10\,796\text{ m}^2$ , and  $11\,166\text{ m}^2$ ).



**Figure 22.** Quarryview residence (left) was removed due to its typology difference and resultant low EUI compared with the remaining post-1980 Lowrise dataset

**Post-1980 Midrise category:** *Progress Student Residence* was removed from the original post-1980 Midrise dataset. This building was identified as an outlier using Tukey's equations (Eq. 1-3) due to its suspiciously high EUI. After close examination, it was determined that some of its conditioned area was designated for Laboratory use, preventing its inclusion in the residences

dataset *North 2 Residence* was removed as its area is much lower (6 166 m<sup>2</sup>) than the rest of the residences part of this sample (11 762 m<sup>2</sup>, 12 152 m<sup>2</sup>, 13 702 m<sup>2</sup>, and 16 279 m<sup>2</sup>).

**Post-1980 Highrise category:** The post-1980 Highrise dataset only included one building; therefore, this dataset was not used to evaluate the prediction methods.

After the inspection of student residences was finalized, the initial dataset decreased from 27 to 21 buildings, categorized into four groups: pre-1980 Lowrise, post-1980 Lowrise, post-1980 Midrise and pre-1980 Highrise. The energy benchmarks and average descriptors of each of these student residence categories can be seen in Table 15.

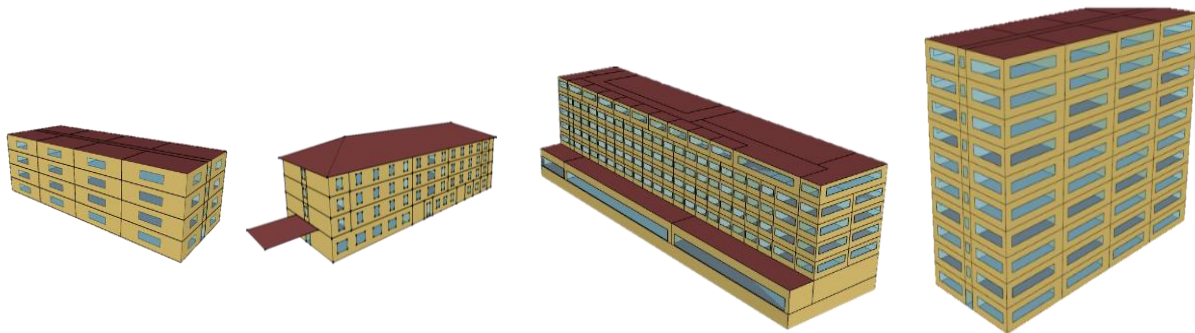
**Table 15.** Samples derived from the classification process with average descriptors. Note that the post-1980 Lowrise category has the largest standard deviation as one of its buildings was identified as an outlier but not removed.

Category	n	ekWh/m <sup>2</sup>	S. dev	Floors	Height	Area	WWR
Pre-1980 Lowrise	4	397	3%	4	13 m	6053 m <sup>2</sup>	30%
Post1980 Lowrise	4	339	12%	4	13 m	9618 m <sup>2</sup>	30%
Post1980 Midrise	4	312	19%	7	21 m	13474 m <sup>2</sup>	30%
Pre-1980 Highrise	8	388	17%	15	43 m	8396 m <sup>2</sup>	30%

With the classification process complete, the next step for predicting aggregate consumption was the characterization of reference templates capable of representing each category (dataset) of buildings, which required a complete set of thermal properties and building systems to be defined for each. The following section summarizes characterization templates defined for classified datasets.

## 5.2 Building Stock Characterization

To simulate the consumption using the *Wireframe* and *Reference* methods, it was necessary to define characterization templates (sets of inputs that represent a type of buildings) for each of the four categories presented in Section 5.1. Collected building characteristics were averaged for each student residence category and compared to U.S. DOE commercial reference models. For review were those DOE models that were built to represent existing buildings in climates like that of Toronto, and that have a similar vintage and operation to that of student residences. The results determined that DOE Small Hotel and Midrise Apartment reference models were most characteristically similar to buildings part of the Lowrise student residence categories, while DOE Large Hotel and Highrise Apartment models were most similar to buildings part of the Midrise and Highrise residence categories. These DOE lodging and apartment models were chosen for review as the models have a similar use to student residences, while also having similar conditioned floor areas. All DOE models (except the Highrise Apartment) were developed to represent pre-1980 and post-1980 existing buildings. DOE refers to these models as *reference building models* and they are used to represent the consumption of existing buildings. As only the Large Hotel reference model is comparable to Midrise and Highrise residences, a Highrise Apartment *prototype* model was considered. The Highrise Apartment prototype represents a building that “just meets” minimum ASHRAE 2004 requirements. The DOE refers to these types of models as *prototype building models* and they are used to measure improvements in the building code. Figure 23 presents the 3D geometries of reviewed DOE models.



**Figure 23.** Building geometry and shading devices from of U.S. DOE models (from left to right): Midrise Apartment, Small Hotel, Large Hotel and Highrise Apartment

*Note that the templates presented in this section are not fully representative of student residences as no building audit data or survey data were used in their development*

### 5.3 Student Residence Characterization Values

The process for selecting the inputs for the pre-1980 Lowrise residence models is explained in detail in this section; several values are consistent across the remaining three categories, and these along with key differences will be discussed in Section 5.4. The full comparison of DOE model inputs and sources for each of the four classified residence categories may be found in **Appendix B**.

Based on the lodging industry practice, hotel guest rooms maintain a 21°C setpoint for both heating and cooling year around [59]. As student rooms predominate in student residence building, it was decided that the models would maintain 21°C for cooling and 21°C for heating year around. Additionally, a floor-to-floor height of 3m, a 30% glazing ratio and a “perimeter/core” offset of 3m have been set for all templates.

#### 5.3.1 Form inputs: pre-1980 Lowrise residence models

The aspect ratio of the U.S. DOE Small Hotel model and the average area derived from the pre-1980 Lowrise residence sample were used to represent the *Reference* method model, while the *Wireframe* method models use real building area footprints and heights to represent the form of student residence buildings. The aspect ratio of the Small Hotel was selected as its shape was more representative of student residences in the pre-1980 Lowrise category. Form characterization inputs defined for the pre-1980 Lowrise category can be seen in Table 16.

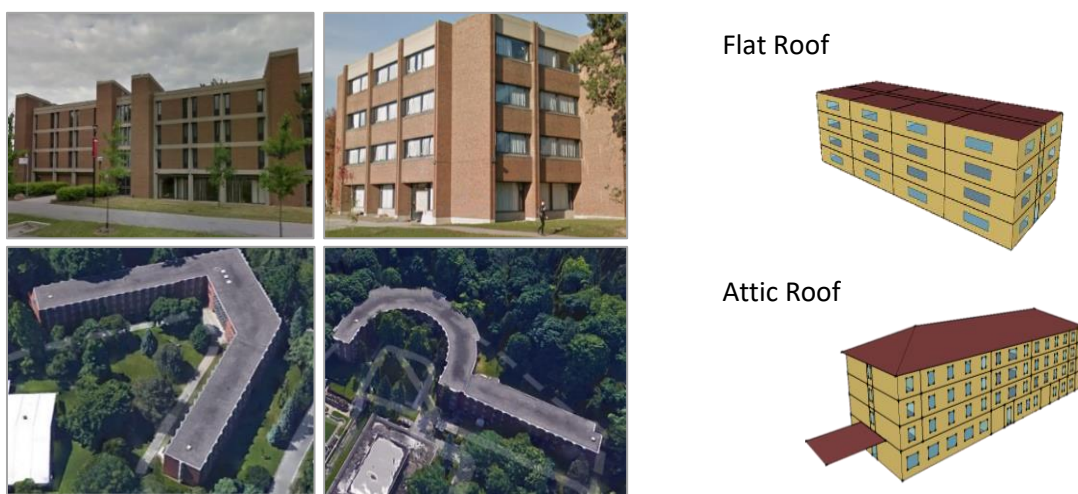
**Table 16.** Pre1980 Lowrise Form characterization inputs

Characterization inputs	Reference method	Wireframe method
Total conditioned area	6053 m <sup>2</sup> *	GIS defined
Number of floors	4	GIS defined
Building height	12 m	GIS defined
Aspect Ratio	3	GIS defined
Window to wall ratio	30%	30%
Shading	None	None
Floor to floor height	3 m	3 m
Building shape	Rectangle	GIS defined

\*Value used to determine the building EUI, which is multiplied by the actual building area to estimate the energy use

### 5.3.2 Fabric inputs: pre-1980 Lowrise residence models

Between the selected U.S. DOE models, the construction assemblies with the most significant differences were the exterior roof, the ceiling, and the interior floor. The Small Hotel has an unconditioned insulated attic space while the Midrise Apartment has an *Insulated Entirely Above Deck* (IEAD) roof type. This variation does not affect the thermal performance of the assembly as the presented resistivity values are identical for both models. As most pre-1980 Lowrise residences in the sample seem to have a flat roof (Figure 24) the IEAD construction assembly was used to characterize the exterior roof of pre-1980 Lowrise residences.



**Figure 24.** Pre1980 Lowrise Residence buildings showing typical flat roof condition

The Midrise Apartment model considers the outermost layer of its ceilings and interior floors to be adiabatic, therefore, there is no heat transfer happening between the levels of the building. This assumption is inappropriate, as adiabatic conditions are a simplifying assumption rather than a real condition and contradict observed heat transfer between floors. The ceiling and interior floor assemblies from the Small Hotel model were thus used to characterize the same assemblies of the pre-1980 Lowrise residence models. The internal mass properties of the Small Hotel and Midrise models are identical and were therefore used without modification to characterize the internal mass of the pre-1980 Lowrise models. An internal mass is used to specify material parameters and area of items within a space that are important to heat transfer calculations (*i.e. furniture within a space*). A summary of fabric inputs selected for pre-1980 Lowrise residence buildings can be seen in Table 17.

**Table 17.** Pre-1980 Lowrise Residence Fabric characterization inputs for both, the Reference and Wireframe models

Characterization inputs	Assembly name	Assembly details
Ground floor slab	ext-slab-mass	1.22 m <sup>2</sup> *K/W
Exterior roof	Typical IEAD Roof R-16.67	2.99 m <sup>2</sup> *K/W
Exterior wall	Insulated Steel Framed Exterior Wall R-6.9	1.22 m <sup>2</sup> *K/W
Ceiling	Typical Interior Ceiling	-
Interior walls	Typical Interior Wall	-
Interior floor	Typical Interior Floor	-
Internal mass	Interior Furnishings	-
U-Factor		3.53 W/m <sup>2</sup> *K
Glazing	SHGC	0.41
	Visible transmittance	0.32
Air tightness	ACH@75Pa	0.92

The Small Hotel has a set infiltration rate of 0.95 Air Changes per Hour (ACH) while the Midrise Apartment has 0.92 ACH. Given that the infiltration rates for the Small Hotel are from previous air tightness studies performed on buildings of various operations and climates [31] while those for the Midrise Apartment are based on audits performed in New York Apartments (climate similar to Toronto) [60], the 0.92 ACH of the Midrise model was used to characterize the infiltration rate of the pre-1980 Lowrise residence models.

### 5.3.3 Program inputs: Space activity for pre-1980 Lowrise residence models

Space activities of the Midrise Apartment model were selected to represent Lowrise residence building activities. From the review, it was determined that the Small Hotel model and Ryerson's Pitman Hall residence activities such as parking structures, gym, and food services, are less common in smaller residence buildings. Although laundry and washroom activities (seen in both buildings) are likely to be seen in Lowrise residences, inputs of the Midrise Apartment model already consider laundry and washroom loads. For this reason, Lowrise residence reference models were characterized with the activity breakdowns seen in the Midrise Apartment model (87% apartment (student rooms), 10% corridors and 3% office space).

**Table 18.** Space activity breakdown for Lowrise residence reference models

Space activity name	Area
Student rooms	87%
Corridors	10%
Office space	3%

#### 5.3.4 Program input: Occupant densities for pre-1980 Lowrise residence models

Occupant densities found in the DOE Midrise Apartment model were used to characterize the occupancy rates of Lowrise residence models. Midrise Apartment occupancy rates assume higher occupancy densities than the Small Hotel model, and therefore selected as these better represent occupancy patterns seen in student residences. In the Lowrise models, 87% of the space is designated to student room use, 10% to corridors and 3% to office space. Taking the weighted average of the occupancy density of these spaces resulted in a 32 m<sup>2</sup>/person density (Table 19).

**Table 19.** Occupancy for pre-1980 Lowrise residence models

Space activity	Area (%)	Occupancy from DOE models (m <sup>2</sup> /pax)	Weighted Occupancy (m <sup>2</sup> /pax)
Student room	87	35.3	30.7
Office	3	44	1.3
Corridor	10	0	0.0
Weighted Average Pre-1980 Lowrise total peak occupancy density			32

#### 5.3.5 Program input: Ventilation rates for pre-1980 Lowrise residence models

The Small Hotel and Midrise Apartment reference models assume that all vintages meet ventilation requirements of Standard 62-2001. This assumption was set by DOE model developers as there were no reliable data for older buildings at the time of the models' development. Ventilation rates found in the DOE Midrise Apartment model were used to characterize ventilation requirements of the Lowrise residence models as these were assumed to better represent the space activities seen in pre-1980 Lowrise residence models. Taking the weighted average of the ventilation requirements for each space (apartment, office, and corridor) resulted in a continuous ventilation rate calculated at 0.45 L/s/m<sup>2</sup> (Table 20).

**Table 20.** Ventilation rates for pre-1980 Lowrise residence models

Space activity	Area (%)	Ventilation rate from DOE models (L/s/m <sup>2</sup> )	Weighted Ventilation rate (L/s/m <sup>2</sup> )
Student dormitory	87	0.48	0.42
Office	3	0.23	0.01
Corridor	10	0.25	0.03
Weighted Average Pre-1980 Lowrise total ventilation rate			0.45



### 5.3.6 Program input: Lighting loads for pre-1980 Lowrise residence model

Lighting loads for pre-1980 Lowrise student residence models are based on activities seen in both the Small-hotel and Midrise Apartment models. The Small Hotel guest room and Midrise apartment lighting power densities were added and averaged out, resulting in 11.29 W/m<sup>2</sup> loads. This value was used to represent student room loads, while office and corridor loads were the same for both Midrise and Small Hotel models. Taking the weighted average of selected lighting power densities (LPD) resulted in a calculated load 11.40W/m<sup>2</sup> (Table 21).

**Table 21.** Lighting rates for pre-1980 Lowrise residence models

Space activity	Area (%)	LPD from DOE models (W/m <sup>2</sup> )	Weighted LPD (W/m <sup>2</sup> )
Student dormitory	87	11.29	9.82
Office	3	22	0.66
Corridor	10	9.2	0.92
Weighted Average Pre-1980 Lowrise total lighting power density			11.40

### 5.3.7 Program input: Plug and process loads for pre-1980 Lowrise residence model

Plug and process loads for pre-1980 Lowrise student residence models are based on activities seen in both the Small-hotel and Midrise Apartment models. The Small Hotel guest room and Midrise apartment space plug load densities were added and averaged out, resulting in 9.85 W/m<sup>2</sup> loads. This value was used to represent student room loads, while office and corridor loads had the same values in both Midrise and Small Hotel models. Taking the weighted average of selected plug load densities and adding a daily elevator load of 0.07W/m<sup>2</sup> resulted in a calculated peak plug load density of 9 W/m<sup>2</sup> (Table 22).

**Table 22.** Plug and process loads for pre-1980 Lowrise residence models

Space activity	Area (%)	Plug load from DOE models (W/m <sup>2</sup> )	Weighted Plug load (W/m <sup>2</sup> )
Student dormitory	87%	9.85	8.57
Office	3%	12.9	0.39
Corridor	10%	0	0.00
Weighted Average Pre-1980 Lowrise total plug load (W/m <sup>2</sup> )			9

Electricity consumption of the elevators used in Low-rise residence models are based on a study by Sachs [61]. The study demonstrates that Low-rise hydraulic elevators doing 100,000 door

openings consume 1,900 kWh per year. Sachs results were used to characterize Lodging Commercial reference models [59] and all student residence models.

### 5.3.8 Program input: Water system rates for pre-1980 Lowrise residence model

Hot water usage is modelled based on a defined peak hot water flow rate and hot water usage schedules. The peak hot water flow rates for DOE reference models were calculated using “typical” daily water usage rates. The Small Hotel guest room space activity has a typical hot water use of 53 L/day as described in the *2007 ASHRAE Handbook: HVAC Applications* [62]. The Small Hotel model has a gas-fired storage water heater with a hot water recirculation loop to provide hot water to guest rooms and laundry space types. This assumption is based on 2003 CBECS data, which shows that the most typical fuel for service hot water in hotels with less than 80 rooms is natural gas [59]. Domestic hot water rates (DHW) for the Midrise Apartment model represent the use of showers, baths, sinks, dishwasher, and clothes washer. The average daily water consumption of each DHW use of the model is based on *Building America* equations. DHW usage for the clothes washer and dryer are based on studies by NREL while showers, baths, and sinks are based on the average of three domestic hot water studies [63].

Water system rates selected for pre-1980 Lowrise models (Table 23) are based on rates of the Small Hotel, which are higher than the Midrise Apartment rates. The larger water system rate was chosen to consider inefficient water systems which are more likely to be seen in older buildings. It was later decided to use a higher rate (0.19 L/h/m<sup>2</sup>) as models were underpredicting water system loads.

**Table 23.** Water system rates for pre-1980 Lowrise residence models

Space activity	Area (%)	Water system load from DOE models (L/h/m <sup>2</sup> )	Weighted Water system Load (L/h/m <sup>2</sup> )
Student dormitory	87%	0.20	0.17
Office	3%	0	0.00
Corridor	10%	0	0.00
Weighted Average Pre-1980 Lowrise total water system rate			0.17

### 5.3.9 Equipment input: HVAC system characteristics for pre-1980 Lowrise residence model

The Small Hotel has a COP 3.4 for cooling and 0.8 for heating [59]. The Midrise Apartment model specifies a 0.8 efficiency for gas furnaces and a COP of 3.4 for cooling [63] Equipment

COP for pre-1980 Lowrise models was set as 0.8 for heating, and 3.4 for cooling as both DOE modes had these efficiencies. No economizer or natural ventilation was defined for the models.

#### **5.4 Additional Template Development**

The remaining three templates were developed following a similar approach to that presented for the pre-1980 Lowrise. All Lowrise residence templates consistently use an aspect ratio of 3 (based on the Midrise Apartment), while the Midrise and Highrise residences use an aspect ratio of 3.9. The 3.9 aspect ratio represents the average ratio of the Large Hotel and Highrise Apartment DOE models.

As mentioned above, the infiltration rates for the Midrise Apartment are based on audits performed in New York Apartments and were therefore selected to characterize the rates of pre-1980 Lowrise residences. As the infiltration rates of the Midrise Apartment did not vary with vintage, the same 0.92 ACH of the pre-1980 Lowrise models is specified for post-1980 Lowrise models. The infiltration rate of 0.60 ACH from the Large Hotel model was used for both Midrise and Highrise models. The infiltration rate of the Highrise Apartment was not considered as this DOE model was built to meet minimum 2004 ASHRAE requirements and most student residences studied in this thesis were built prior to 2004.

According to reviewed DOE model inputs, construction assemblies vary based on the model type (*i.e.* Midrise Apartment, Small Hotel). However, the thermal resistivity properties of the construction assemblies only vary according to a model's vintage. Although the pre-1980 Small Hotel model has a different construction assembly for exterior walls (Insulated Steel Framed Exterior Wall R-6.9) to that of the pre-1980 Large Hotel (TYPICAL INSULATED EXTERIOR MASS WALL R-6.9), their thermal efficiency remains the same. This was the case for all construction assemblies, including glazing, roof, and slabs. Therefore, all pre-1980 student residences have the same thermal resistivity values, and all post-1980 student residences have the same thermal resistivity values. As only pre-1980 thermal resistivities have been presented, below are the post-1980 Midrise construction assemblies with their thermal properties (Table 24). Note that all DOE models, regardless of their operation or vintage, had an internal mass with standard 6-inch wood properties. Therefore, the same properties were applied to the floors of all student residence models.

**Table 24.** Post-1980 Midrise residence *fabric* inputs

Characterization inputs	Assembly name	Assembly details
Ground floor slab	ext-slab	0.54 m <sup>2</sup> *K/W
Exterior roof	IEAD Res Roof	3.97 m <sup>2</sup> *K/W
Exterior wall	Steel Frame Res Ext Wall	2.48 m <sup>2</sup> *K/W
Ceiling	INT-FLOOR-UNDERSIDE	-
Interior walls	Int-walls	-
Interior floor	INT-FLOOR-TOPSIDE	-
Internal mass	Interior Furnishings	-
Glazing system	U-Factor	2.95 W/m <sup>2</sup> *K
	SHGC	0.39
	Visible transmittance	0.31
Air tightness	ACH@75Pa	0.6

The HVAC systems of compared DOE models vary based on model vintage, operation, and size. However, the thermal efficiency of the models does not necessarily vary. No economizer or natural ventilation was defined in DOE models nor student residences.

The following subsections highlight key differences between residence models. The resultant templates for all four categories are provided in **Appendix C**.

#### 5.4.1 Post-1980 Lowrise

The post-1980 Lowrise template differs from the pre-1980 Lowrise in that post-1980 Midrise Apartment and Small Hotel reference models were used to inform its input values. Several input values remain the same, such as infiltration rates, aspect ratio, and space activity breakdown. The post-1980 Lowrise model has 87% of its space designated to student rooms, 10% to corridors and 3% to offices. Because space activity breakdowns are used to define internal load values, many remain the same as those specified in pre-1980 Lowrise templates. For example, the occupancy of the pre-1980 and post-1980 Small Hotel and Midrise Apartment model are based on ASHRAE 62.1-2004. Therefore, if the space activity is the same as that of pre-1980 Lowrise models, and they also use ASHRAE 62.1-2004 to define occupancy, the same value will result (32m<sup>2</sup>/pax). This was also the case for ventilation rates (ASHRAE 62-1999), lighting loads (ASHRAE 90.1 - 1989). However, to have the newer buildings be more energy efficient, rather than using the average LPD of Hotel guest rooms and Midrise apartments (as in pre-1980 Lowrise), only the lower LPD value of the two models was considered.

Taking the weighted average of selected light load densities resulted in a calculated power density of  $5\text{W/m}^2$  (Table 25), lower than the  $11.40\text{ W/m}^2$  specified in pre-1980 Lowrise templates.

**Table 25.** Lighting rates for pre-1980 Lowrise residence models

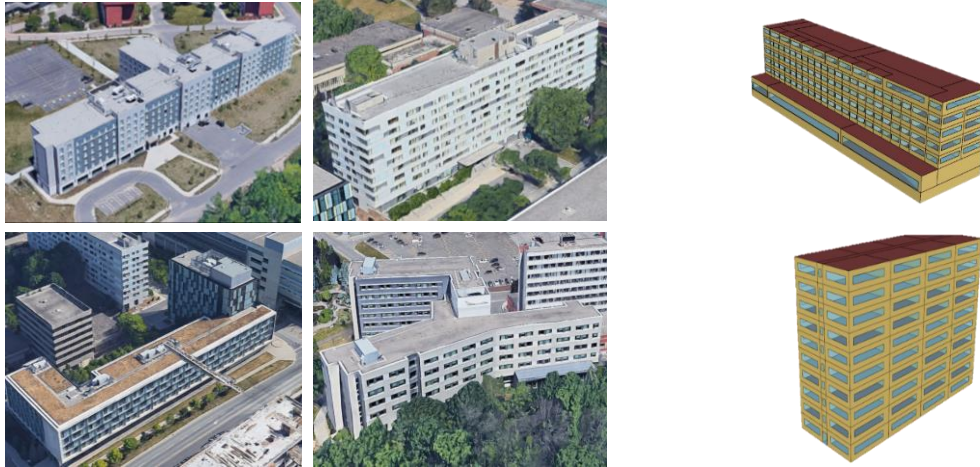
Space activity	Area (%)	LPD from DOE models ( $\text{W/m}^2$ )	Weighted LPD ( $\text{W/m}^2$ )
Student dormitory	87	3.88	3.38
Office	3	22	0.66
Corridor	10	9.2	0.92
Weighted Average Post-1980 Lowrise total lighting power density			4.96

Ventilation rates and water system rates, and process loads are the same for pre-1980 Lowrise models and post-1980 models, as shown above. Regarding the equipment of the DOE models, equipment type does vary, however, both pre-1980 and post-1980 DOE models have the same HVAC efficiencies (except the hot water system efficiency which is lower for post-1980 (0.78) models). The pre-1980 DOE hot water values come from analysis of existing buildings (Winiarski and Halverson, 2008) while the post-1980 DOE hot water values come from ASHRAE Standard 90.1 1989. Although one would expect newer buildings to be more efficient, studies suggest that post-1980 have slightly lower hot water efficiency. This could be because pre-1980 models have had system upgrades, while post-1980 have not. Therefore the 0.78 efficiency for hot water loads was specified for post-1980 Lowrise models.

#### 5.4.2 Post-1980 Midrise

The post-1980 Midrise template combines the DOE 2004 Highrise Apartment and post-1980 Large Hotel as these models were representative of buildings from the Midrise category (Figure 25). As discussed in Section 5.1, the 2004 Highrise Apartment *prototype model* was used as no other post-1980 reference model with similar operation to student residences was available.

Table 26 shows the comparison of the Large Hotel, Highrise Apartment and post-1980 Midrise Form values. As seen in this table, the Large Hotel is very similar to post-1980 Midrise residence characteristics. However, the Midrise residence is larger than both Large Hotel and Highrise Apartment DOE models. For simplicity's sake, it was decided not to include any underground walls in the 3D models. However, because basements are typical in these types of buildings, their internal loads were considered in estimating the total load of Midrise residences.



**Figure 25.** Post-1980 Midrise buildings compared to post-1980 Large Hotel (top) and 2004 Highrise DOE models

**Table 26.** Building Form comparison between DOE models and Midrise student residence values

Building form variables	Large Hotel	Highrise Apartment	Midrise
Vintage	Post 1980	2004	Post 1980
Total conditioned area	11,345 m <sup>2</sup>	7836 m <sup>2</sup>	13474 m <sup>2</sup>
Number of floors	6 + basement	10	7
Building height	22 m	30.5 m	21 m
Aspect Ratio	5.1	2.75	n/a
Window to wall ratio	30%	30%	30%
Shading	None	None	None
Floor to floor height	3.05 m	3.05m	n/a
Building shape	Rectangle	Rectangle	n/a

As mentioned previously, the variation of space activity in a building directly affects its energy consumption as the use given to a space influences its internal loads. Therefore, space activities between the Large Hotel and the High-rise models were compared to identify their differences (Table 27). Additionally, Pitman Hall space activities were reviewed (Table 28). All three sources were considered in the selection of space activities that represent Midrise student residences.

**Table 27.** Programmatic breakdown of the Small Hotel and Mid-rise Apartment commercial reference models

Space activity	Large Hotel		High-rise Apartment	
Basement	1979 m <sup>2</sup>	17 %	-	-
Retail	145 m <sup>2</sup>	1 %	-	-
Mechanical	164 m <sup>2</sup>	1 %	-	-
Storage	95 m <sup>2</sup>	1 %	-	-
Laundry	78 m <sup>2</sup>	1 %	-	-
Cafe	189 m <sup>2</sup>	2 %	-	-
Lobby / office	1308 m <sup>2</sup>	12 %	88 m <sup>2</sup>	1 %
Corridor	1970 m <sup>2</sup>	17 %	776 m <sup>2</sup>	10 %
Dining	332 m <sup>2</sup>	3 %	-	-
Banquet	332 m <sup>2</sup>	3 %	-	-
Kitchen	103 m <sup>2</sup>	1 %	-	-
Guest room/Apartment	4650 m <sup>2</sup>	41 %	6971 m <sup>2</sup>	89 %
Total building area	11,345 m <sup>2</sup>		7836 m <sup>2</sup>	

**Table 28.** Pitman Hall space activity breakdown

Space activity	Area (m <sup>2</sup> )	Area (%)
Administrative offices	175	1%
Common use	1251	6%
Food services	741	3%
Residence living space	9305	43%
Residence service space	786	4%
Washrooms	393	2%
Corridors	4313	20%
Non- assignable space	2148	10%
Parking structure	2427	11%
Total building area	21,538 m <sup>2</sup>	100%

Pitman Hall is much larger in size than reviewed DOE models, but many of its space activities are similar. For example, all models have administrative office spaces, living spaces, and corridors. The largest difference between DOE models is that the Highrise Apartment does not consider kitchen, banquets, or laundry space activities, which are commonly seen in student residences (Table 28). Considering this information, it was decided to define the space activity of post-1980 Midrise models as presented in Table 29.

**Table 29.** Space activity breakdown for Midrise Residence reference models

Space activity	Area (%)
Student room	45%
Corridors	20%
Office space	5%
Lobby	5%
Kitchen	5%
Banquet/Cafe	8%
Basement	10%
Washrooms	2%

Occupancy values defined for Midrise student residences are based on values of three DOE models. Occupancy values of the Large Hotel and Highrise models are based on ASHRAE Standard 62.1-2004, therefore values do not differ significantly. Large Hotel values were used to define the Midrise occupancy of all activities except for office and washroom activities. The office activity specifications of the Large Hotel represent a front desk office/lobby, while the office space of the Highrise model represents a typical apartment complex office (more similar to that of a student residence). Therefore, the occupancy of the Highrise office activity was selected to represent the same activity in Midrise models. Although washrooms are common in most buildings, no space was assigned for this activity in the reviewed DOE models. To specify an occupancy density to the defined washroom space, the occupancy density of a DOE reference model for K-12 school washrooms was used. Taking the weighted average of the occupancy density of Midrise spaces resulted in a 19 m<sup>2</sup>/person density (Table 30).

**Table 30.** Occupancy density for post-1980 Midrise residence models

Space activity	Area (%)	Occupancy from DOE models (m <sup>2</sup> /pax)	Weighted Occupancy (m <sup>2</sup> /pax)
Student dormitory	45%	26	11.7
Office	5%	44	2.2
Corridor	20%	0	0.0
Lobby	5%	3	0.2
Kitchen	5%	18.5	0.9
Banquet/Cafe	8%	1.4	0.1
Basement	10%	37.1	3.7
Washroom	2%	10	0.2
Weighted Average Post-1980 Midrise total peak occupancy density			19

Like occupant densities, ventilation rates are based on the three DOE models. Ventilation rates of the Large Hotel and Highrise Apartment models are based on ASHRAE 62-1999;



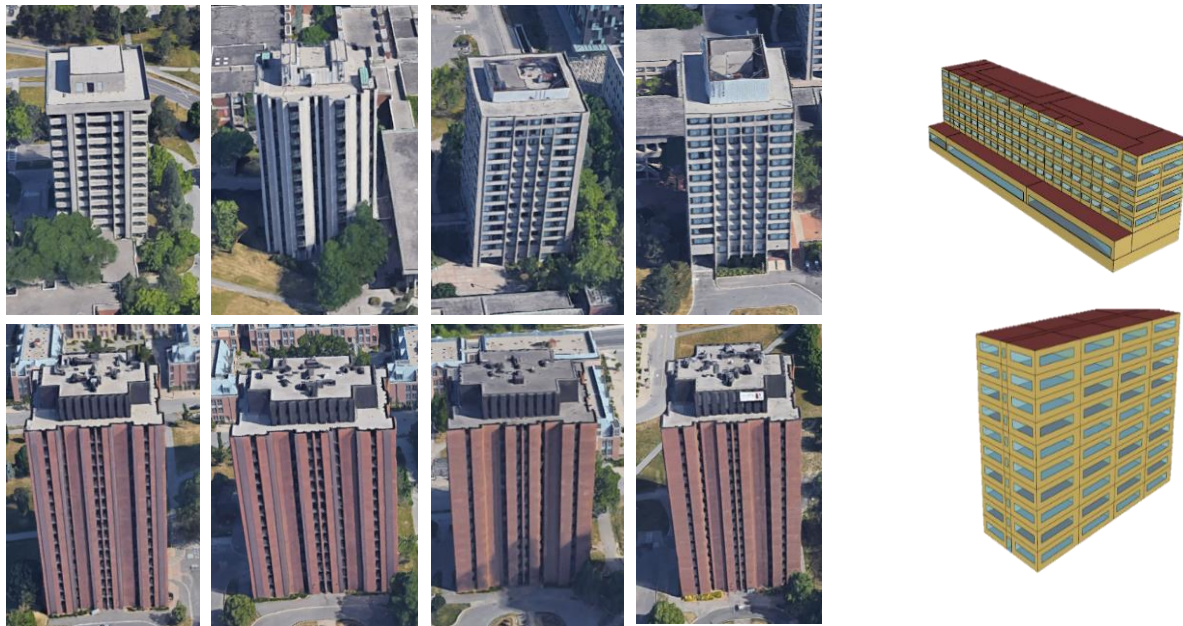
therefore, their values do not differ significantly. Large Hotel values were used to define ventilation rates of all activities except for office and washroom activities. Office and washroom ventilation rates are based on Highrise office and K-12 washroom rates respectively. Taking the weighted average of the ventilation requirements for each space resulted in an occupancy dependent ventilation rate of  $0.93 \text{ L/s/m}^2$ . Occupancy dependent rates were selected for Midrise models as kitchen and banquet ventilation loads vary substantially with occupancy.

Lighting, process, and water system loads follow the same structure which was used for the occupancy and ventilation rates of the post-1980 Midrise models. The most noticeable difference is that to define LPD of student rooms, the apartment space of the Highrise model was used instead of the LPD of Large Hotel guest rooms. This decision was made so that the lighting load of post-1980 Midrise models was more representative of newer buildings. Regarding the process and plug load densities, a larger elevator load ( $4,161 \text{ kWh/yr}$ ) than that used in Lowrise residence models was used to represent elevators in Midrise models. This load is also based on Sachs elevator consumption study [59]. Selected characterization values resulted in a total peak load LPD of  $9.43 \text{ W/m}^2$ , a  $14.6 \text{ W/m}^2$  for plug loads, and a  $0.18 \text{ L/h/m}^2$  for hot water consumption. Through initial simulations of post-1980 Midrise models, it was determined that peak loads should be adjusted. This resulted in a new total peak load LPD of  $13 \text{ W/m}^2$ , an  $18 \text{ W/m}^2$  for plug loads, and a  $0.2 \text{ L/h/m}^2$  for hot water consumption.

Regarding the HVAC systems, a COP of 3.4 for cooling and 0.8 for heating were selected to represent post-1980 Midrise models. Although the selected COP of 3.4 is based on the 2004 Highrise Apartment efficiency (much better than the Large Hotel COP of 2.64), it was decided to apply the higher COP to Midrise models, so these would better represent newer buildings. Again, no economizer or natural ventilation was defined for the models.

### **5.4.3 Pre-1980 Highrise**

The pre-1980 Highrise template was developed by combining the DOE 2004 Highrise Apartment and pre-1980 Large Hotel, as these models were representative of buildings from the Highrise category (Figure 26). The 2004 Highrise was used since no other pre-1980 reference model with similar operation to student residences was available.



**Figure 26.** Pre-1980 Highrise buildings compared to pre-1980 Large Hotel (top) and 2004 Highrise DOE models

Table 31 shows the comparison of the Large Hotel, Highrise Apartment, and pre-1980 Highrise Form values. As seen in this table, the form of the Highrise Apartment is most like that of the pre-1980 Highrise student residence. For simplicity's sake, it was decided not to include any underground walls in the 3D models.

**Table 31.** Building *form* comparison between DOE models and Highrise student residence values

Building form variables	Large Hotel	Highrise Apartment	Highrise
Vintage	Post 1980	2004	Pre 1980
Total conditioned area	11,345 m <sup>2</sup>	7836 m <sup>2</sup>	8396m <sup>2</sup>
Number of floors	6 + basement	10	15
Building height	22 m	30.5 m	43 m
Aspect Ratio	5.1	2.75	n/a
Window to wall ratio	30%	30%	30%
Shading	None	None	None
Floor to floor height	3.05 m	3.05m	n/a
Building shape	Rectangle	Rectangle	n/a

Space activities between Pitman Hall, the Large Hotel and the High-rise Apartment were compared to identify their differences. Although space activities and their percentages do not differ from those presented in Table 27 and Table 28, the percentage of space activities for Highrise residences are different to those used for Midrise residences. The difference simply represents the expected variation in area between Highrise and Midrise space activities. Space activities selected to represent pre-1980 Highrise buildings can be seen in Table 32.

**Table 32.** Space activity breakdown for Highrise residence reference models

Space activity	Area (%)
Student dormitory	50%
Corridors	18%
Office space	5%
Lobby	2%
Kitchen	3%
Banquet/Cafe	10%
Basement	8%
Washrooms	4%

Occupancy densities defined for Highrise student residences are based on the same values used to represent post-1980 Midrise occupancy. Therefore, the occupancy density of the Highrise spaces resulted in the same 19 m<sup>2</sup>/person density (Table 33).

**Table 33.** Occupancy density for post-1980 Midrise residence models

Space activity	Area (%)	Occupancy from DOE models (m <sup>2</sup> /pax)	Weighted Occupancy (m <sup>2</sup> /pax)
Student dormitory	50%	26	13.0
Office	5%	44	2.2
Corridor	18%	0	0.0
Lobby	2%	3	0.1
Kitchen	3%	18.5	0.6
Banquet/Cafe	10%	1.4	0.1
Basement	8%	37.1	3.0
Washroom	4%	10	0.4
Weighted Average Pre-1980 Highrise total peak occupancy density			19

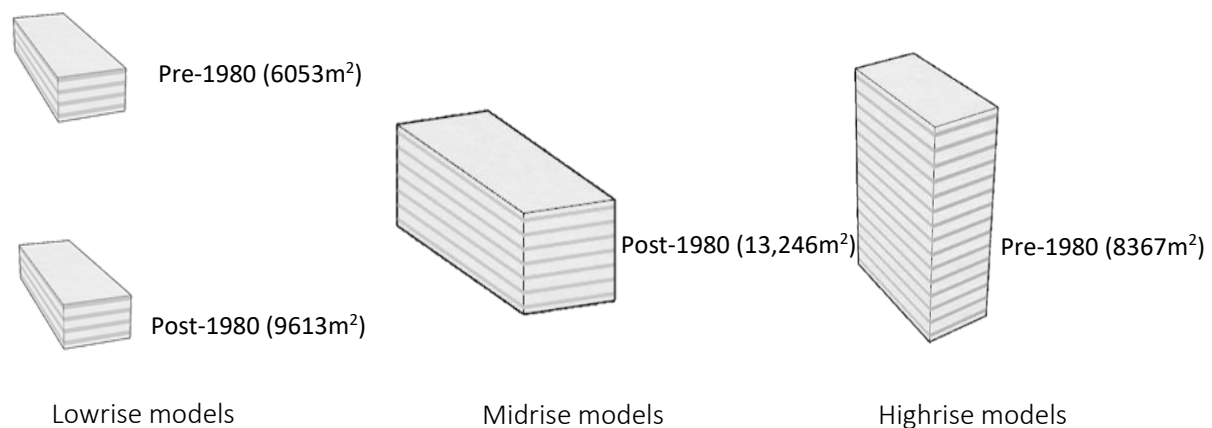
Ventilation rates are also based on the same sources used to represent Midrise residence rates. However, due to the percentage variation in space activities, the ventilation rate increased. The weighted average of the ventilation requirements for each space resulted in an occupancy dependent ventilation rate of 0.97 L/s/m<sup>2</sup>. Occupancy dependent ventilation rates were selected for Midrise models as kitchen and banquet loads vary substantially with occupancy.

Unlike ventilation and occupancy, lighting loads between the DOE models do differ as they use diverse sources to define their LPD. The pre-1980 Large Hotel lighting power densities are based on ASHRAE 90.1-1989, while the 2004 Highrise Apartment LPD are based on ASHRAE 90.1-2004. As the LPD of the Large Hotel are more representative of older buildings, these were primarily considered to represent pre-1980 Highrise residence lighting loads. The pre-1980 Highrise student residence template uses lighting densities from the Large Hotel for all space

activities except for student room, office, and washroom spaces. The lighting load of student rooms comes from the average of the Large Hotel guest room and the 2004 Highrise apartment space. The resultant student room LPD ( $11.43 \text{ W/m}^2$ ) better represents student residences as it assumes that some buildings have gone through lighting retrofits. The office LPD comes from the 2004 Highrise office space as it was more representative of student residences (explained in Section 5.4.2). To specify the lighting loads of the student washroom space, the LPD of DOE reference model for K-12 school washrooms was used. The weighted average of the lighting requirements for each space resulted in an LPD of  $12.72 \text{ W/m}^2$ . Regarding the process and plug load specifications, Large Hotel values were chosen for all spaces except for office and washroom activities. These were based on the 2004 Highrise office values and the K-12 school washroom values. An elevator load of 4,161 kWh/year was used [59], resulting in a total peak plug and process load of  $14.6 \text{ W/m}^2$ . Through initial simulations of pre-1980 Highrise models, it was determined that peak loads should be adjusted, resulting in a new total peak load LPD of  $16 \text{ W/m}^2$  and  $18 \text{ W/m}^2$  for plug loads. Regarding the HVAC systems, the efficiencies of the pre-1980 Large Hotel were considered as this model had the same vintage as the student residences. Therefore, a COP of 2.64 was chosen for cooling and 0.78 for heating. No economizer or natural ventilation was defined for the models.

## 6 Student Residence Model Tuning

The review of DOE commercial reference models resulted in the synthesis of characterization inputs that better represent Ontario student residences. In total, four *baseline* characterization templates were developed from selected inputs to represent pre-1980 Lowrise, post-1980 Lowrise, post-1980 Midrise and pre-1980 Highrise student residence buildings. Preliminary modeling using the *Reference* method (Figure 27) and *baseline* templates resulted in five end-use consumption values. These were normalized based on the area of the model and were compared to normalized end-use consumption values predicted with DOE reference models. If preliminary values were found to be drastically higher or lower than DOE values, models were adjusted accordingly. At this point, it is important to be aware of the intended scope of this study, which is to comprehend prediction differences between two bottom-up methods and understand why they occur. Although models were adjusted, the intention was not to make them equal to MER energy benchmarks but to ensure their end-use consumption was similar to the end-use consumption of reviewed DOE reference models. If models were adjusted according to MER benchmarks using the *Reference* method, it would skew the results for the *Wireframe* method. Therefore, models were adjusted so that the end-use consumption of the student reference models were like that of the DOE models, this to ensure that produced energy breakdowns were representative of buildings that serve as living spaces. The development of these models as *reference models* does not form part of this thesis but rather as future work, requiring field data studies to confirm these assumed inputs.

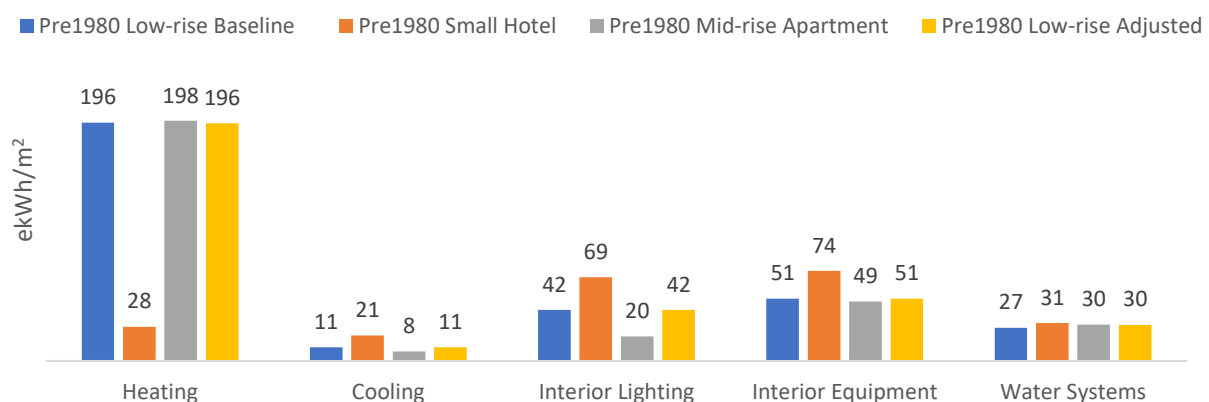


**Figure 27.** Visual representation of student *Reference* method models created with Rhinoceros and UMI

### 6.1.1 Pre-1980 Lowrise residence model adjustment

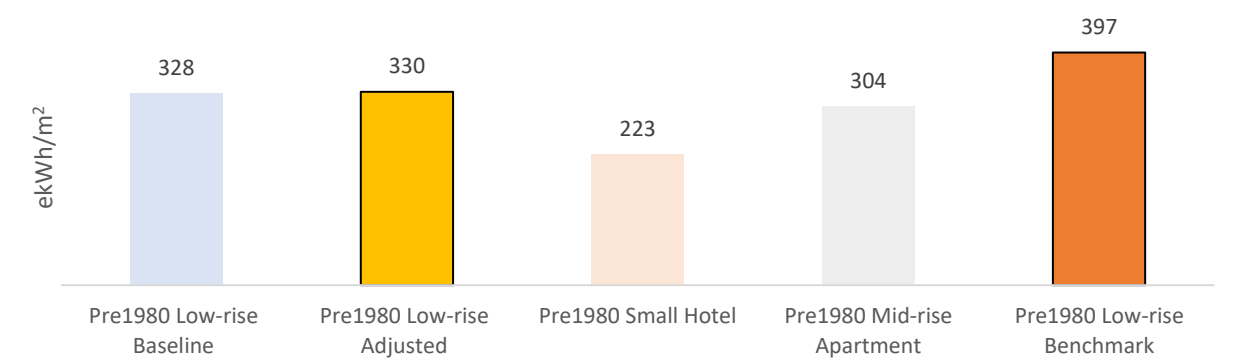
The pre-1980 Lowrise *baseline* characterization template summarized in Section 5.3 was applied using the *Reference* method and resulted in a predicted EUI of 328kWh/m<sup>2</sup> for the pre-1980 Lowrise Residence buildings. This predicted EUI is above both the calculated pre-1980 Small Hotel model EUI (238kWh/m<sup>2</sup>) and the pre-1980 Midrise Apartment model EUI (313kWh/m<sup>2</sup>) results. This is understandable because while the majority of inputs come from the Midrise Apartment model, the less efficient plug and lighting power densities of the Small Hotel guestrooms (14.31 W/m<sup>2</sup>, compared with 5.38 W/m<sup>2</sup> for the Midrise Apartments) were incorporated into the pre-1980 Lowrise template, driving up the overall consumption. It is important for all new template creation to be aware of such significant differences between reference models, even for spaces of similar activity categories.

End-use EUIs of the baseline pre-1980 Lowrise, adjusted pre-1980 Lowrise, pre-1980 Small Hotel and pre-1980 Midrise Apartment models are compared in Figure 28, while the overall EUI comparison is summarized in Figure 29. By reviewing the end-use results, it was determined that the most significant difference between the baseline residence model and the DOE models regards to their hot water load, which is 8.6% and 11% lower than in the Midrise Apartment and Small Hotel models, respectively. Other end-uses are either very similar to those predicted by one of the DOE models (*i.e.* heating use) or fall somewhere between the predicted end-use consumption of both DOE models (*i.e.* equipment, lighting).



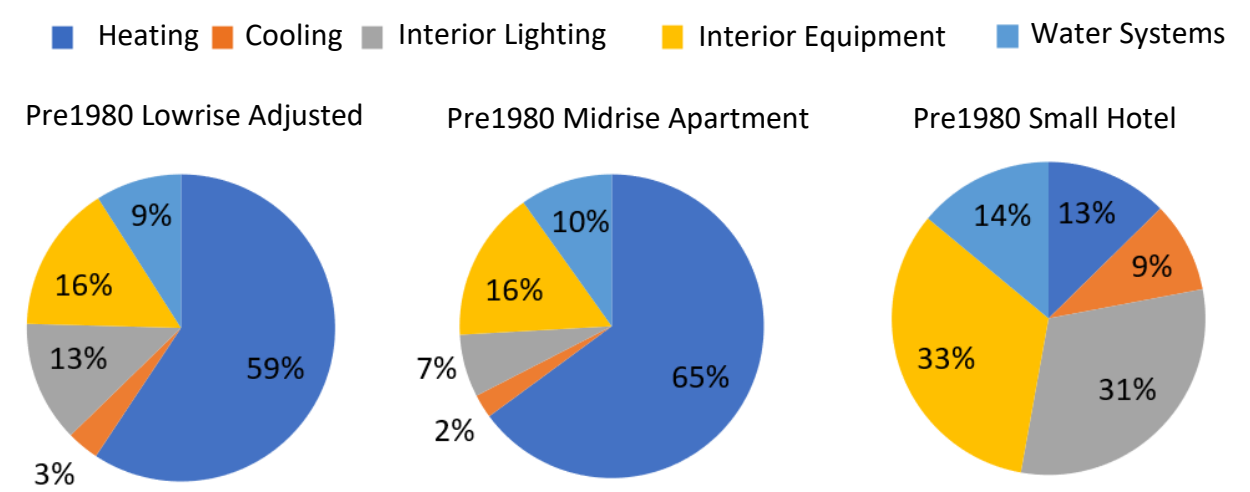
**Figure 28.** End-use comparison of reviewed DOE models and developed residence models. Cooling, lighting, and equipment EUIs predicted with the baseline template are all between the EUI reported for the hotel and the apartment models, therefore, only the water systems end-use was adjusted.

To ensure that pre-1980 Lowrise residences were predicting consumption with similar end-use EUIs to those seen in DOE models, the hot water use of the baseline template was increased from 0.17 L/h/m<sup>2</sup> to 0.19 L/h/m<sup>2</sup>. This adjustment caused a 7.9% increase in water system consumption and 0.6% increase in total site consumption (Figure 29).



**Figure 29.** The predicted EUI of the adjusted pre-1980 Lowrise model is 17% lower than the EUI benchmark of the pre-1980 Lowrise dataset quantified at 397 ekWh/m<sup>2</sup>

Figure 30 reveals that the end-use breakdown predicted with the pre-1980 Lowrise residence model is comparable to the end-use breakdown predicted of the pre-1980 Midrise Apartment model. The discrepancy between the Small Hotel and Apartment models with regards to their heating consumption could not be determined from the analysis of the .IDF provided by DOE.

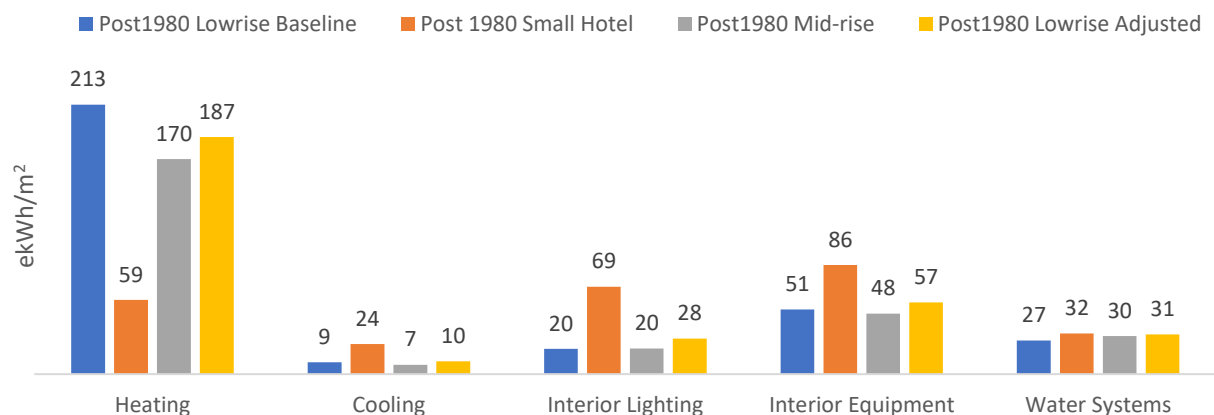


**Figure 30.** Differences between pre-1980 Lowrise adjusted model and the pre-1980 Midrise Apartment model are seen in heating, equipment and lighting uses

### 6.1.2 Post-1980 Lowrise residence model adjustment

The post-1980 Lowrise *baseline* characterization template summarized in Section 5.3 was applied using the *Reference* method, resulting in a predicted EUI of 319kWh/m<sup>2</sup> for post-1980 Lowrise Residence buildings, which is above the post-1980 Small Hotel EUI (269kWh/m<sup>2</sup>) and the post-1980 Midrise Apartment EUI (275kWh/m<sup>2</sup>), respectively.

End-use EUIs of the baseline post-1980 Lowrise, adjusted post-1980 Lowrise, post-1980 Small Hotel and post-1980 Midrise Apartment models are compared in Figure 31, while the overall EUI comparison is summarized in Figure 32. By reviewing the end-use results, it was determined that the most variation between the baseline residence model and the DOE models regards to their heating, lighting, and equipment uses. The heating EUI of the baseline model is 213kWh/m<sup>2</sup>, larger than the apartment model (170kWh/m<sup>2</sup>) and much larger than the hotel model (59kWh/m<sup>2</sup>). The baseline lighting EUI consumption is 20kWh/m<sup>2</sup> similar to that seen in the apartment model (20kWh/m<sup>2</sup>) and lower than that seen in the hotel model (69kWh/m<sup>2</sup>). The baseline equipment EUI is 51kWh/m<sup>2</sup> higher than that seen in the apartment model (48kWh/m<sup>2</sup>) and lower than the hotel model (86kWh/m<sup>2</sup>). Additionally, the baseline water system EUI consumption is roughly 25% lower than the water system EUI predicted by both DOE models.



**Figure 31.** End-use comparison of reviewed DOE models and developed student residence models. Baseline heating EUI is larger than the heating EUI of both DOE models while water system EUIs is lower than both DOE models.

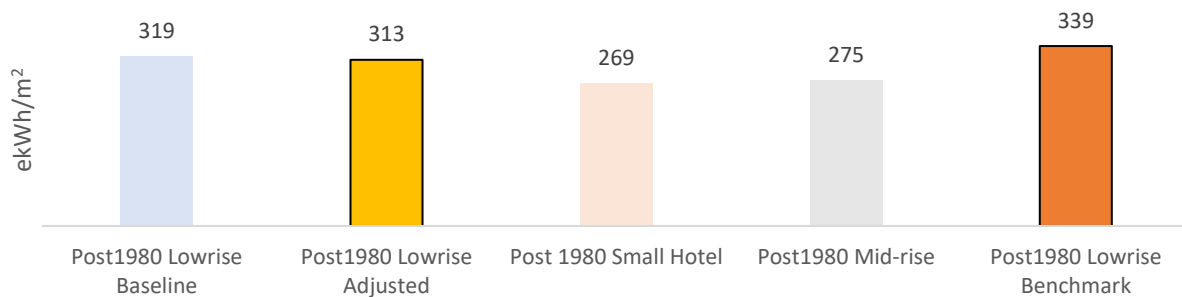
To ensure that post-1980 Lowrise residence models predicted consumption with similar end-use EUIs to those seen in DOE models, the following changes were made to the post-1980 Lowrise characterization template:

- Heating COP was increased from 0.78 to 0.83 to make the models heating more efficient



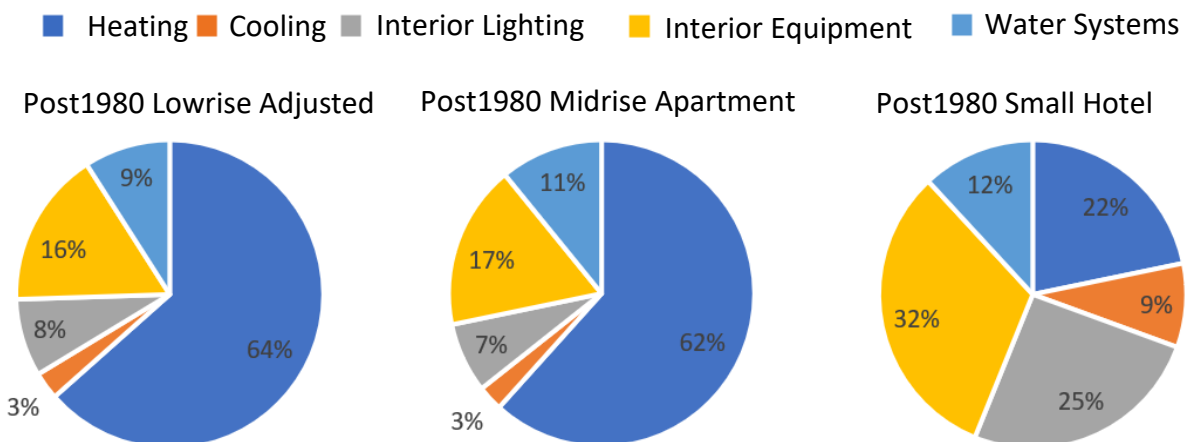
- Lighting power density was increased from 5 W/m<sup>2</sup> to 7 W/m<sup>2</sup>
- Plug load density was increased from 9 W/m<sup>2</sup> to 10 W/m<sup>2</sup>
- Hot water use was increased from .17 L/h/m<sup>2</sup> to .20 L/h/m<sup>2</sup>

These adjustments resulted in a 12% decrease in heating, an 8% increase in cooling, a 41% increase in lighting, a 10% increase in equipment, an 18% increase in water system use, and a 2% decrease in total site consumption (Figure 32). Although the adjustments brought the EUI of the Lowrise residence (313 ekWh/m<sup>2</sup>) further away from the developed benchmark (339 ekWh/m<sup>2</sup>) it was decided that it was more important to have the models predict end-use consumption like the DOE models as their end-uses are more reliable than arbitrary end-uses that would result in a higher model EUI.



**Figure 32.** The predicted EUI of the adjusted post-1980 Lowrise model is 7 % lower than the EUI benchmark of the post-1980 Lowrise Category quantified at 339 ekWh/m<sup>2</sup>

Figure 33 reveals that the end-use breakdown predicted with the post-1980 residence model is comparable to the end-use breakdown produced by the post-1980 Midrise model. The discrepancy between the Small Hotel and Apartment models with regards to their heating consumption could not be determined from the analysis of the .IDF provided by DOE.

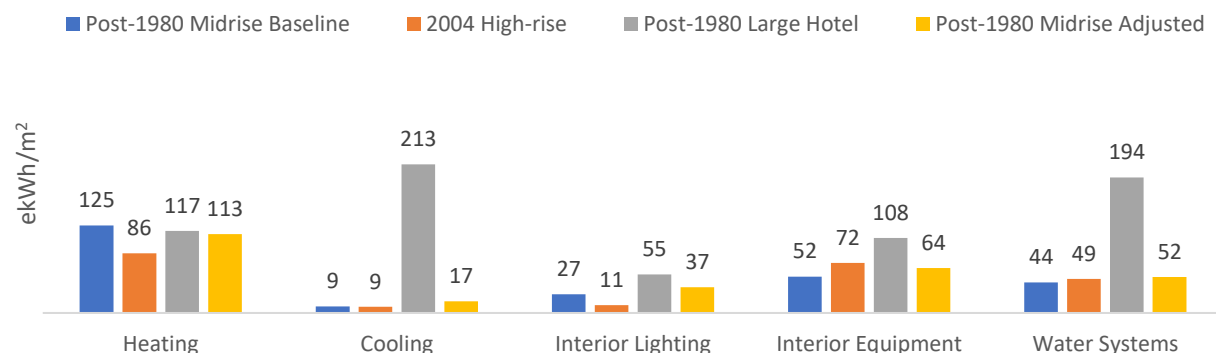


**Figure 33.** Adjusted post-1980 Lowrise and post-1980 Midrise Apartment end-use breakdown

### 6.1.3 Post-1980 Midrise residence model adjustment

The post-1980 Midrise *baseline* characterization template summarized in Section 5.3 was applied using the *Reference* method, resulting in a predicted EUI of 258kWh/m<sup>2</sup> for post-1980 Midrise Residence buildings, which falls between the post-1980 Large Hotel EUI (688kWh/m<sup>2</sup>) and the 2004 Highrise Apartment EUI (226kWh/m<sup>2</sup>).

End-use EUIs of the baseline post-1980 Midrise, adjusted post-1980 Midrise, post-1980 Large Hotel and 2004 Highrise Apartment models are compared in Figure 34 while the overall EUI comparison is summarized in Figure 35. By reviewing the end-use results, it was determined that the most variation between the baseline residence model and the DOE models regards to their cooling, lighting, and water system uses. The cooling EUI of the baseline model is 9kWh/m<sup>2</sup>, equal to the 9kWh/m<sup>2</sup> seen in the apartment model and much lower than the 213kWh/m<sup>2</sup> predicted with the hotel model. Difference in cooling EUI is partially due to the Highrise Apartment having a cooling COP of 3.4 while the Large Hotel has a cooling COP of 2.5. The Large Hotel model also has the largest equipment and lighting EUIs, which result in higher heat gains. Additionally, construction assemblies of DOE models were built to represent buildings of different time periods, resulting in different thermal efficiencies. The baseline lighting EUI consumption is 27kWh/m<sup>2</sup>, lower than the 55kWh/m<sup>2</sup> predicted by the hotel model and larger than the 11kWh/m<sup>2</sup> predicted by the apartment model. The baseline water system EUI consumption is 44kWh/m<sup>2</sup>, lower than the water system EUI predicted by the apartment model of 49kWh/m<sup>2</sup> and much lower than the 194kWh/m<sup>2</sup> predicted by the hotel model. In addition to this, the baseline equipment EUI is roughly 25% and 50% lower than the apartment and large hotel models respectively. The difference in cooling between the Large Hotel and Highrise models is due to different efficiency and construction assemblies when the models are compared to one another.

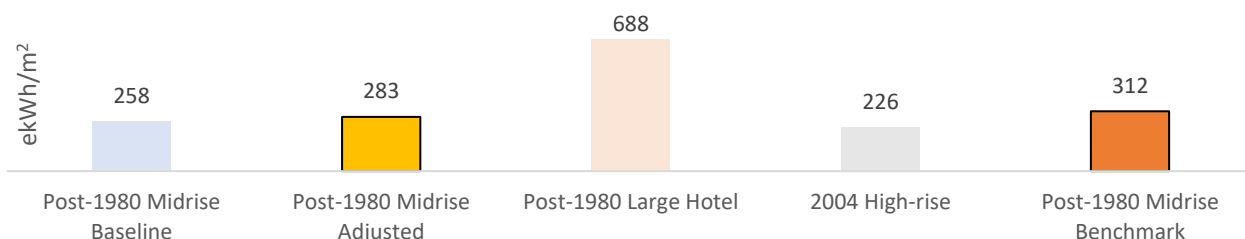


**Figure 34.** Comparison of the end-use EUIs predicted with reviewed DOE and developed residence models

To ensure that post-1980 Midrise residences were predicting consumption with similar end use EUIs to those seen in DOE models, the following changes were done to the post-1980 Midrise characterization template:

- Cooling COP was decreased from 3.4 to 2.5 to match the Large Hotel COP of 2.5. The 3.4 COP is based on 2004 minimum requirements and student residences of this category have a post-1980 vintage which is better represented with the COP of the Large Hotel as it was built to represent post-1980 existing buildings.
- Lighting power density was increased from 9.43 W/m<sup>2</sup> to 13 W/m<sup>2</sup>
- Plug load density was increased from 14.6 W/m<sup>2</sup> to 18 W/m<sup>2</sup>
- Hot water use was increased from .18 L/h/m<sup>2</sup> to .20 L/h/m<sup>2</sup> to match the Large Hotel rate

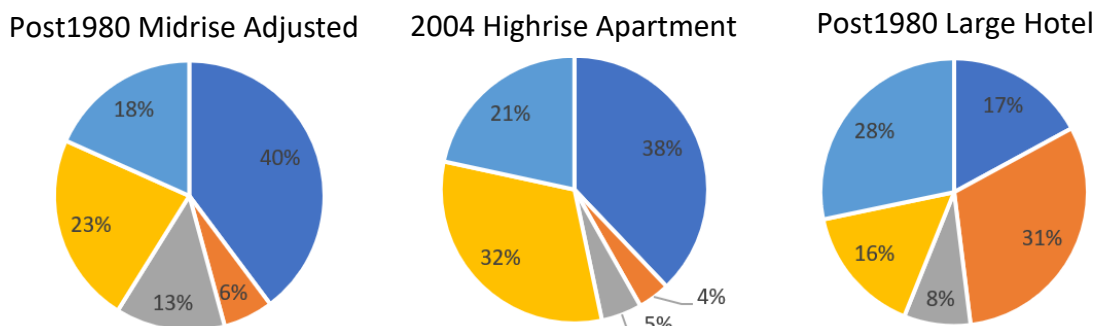
These adjustments caused a 10% decrease in heating EUI, a 79% increase in cooling EUI, a 38% increase in lighting EUI, a 23% increase in equipment EUI, an 18% increase in hot water EUI and an increase of 10% in total EUI (Figure 35).



**Figure 35.** The predicted EUI of the adjusted post-1980 Midrise model is 9% lower than the EUI benchmark of the post-1980 Midrise Category quantified at 312 ekWh/m<sup>2</sup>

Figure 36 reveals that the end-use breakdown predicted with the post-1980 residence model is comparable to the end-use breakdown produced with the 2004 Highrise apartment model.

■ Heating ■ Cooling ■ Interior Lighting ■ Interior Equipment ■ Water Systems

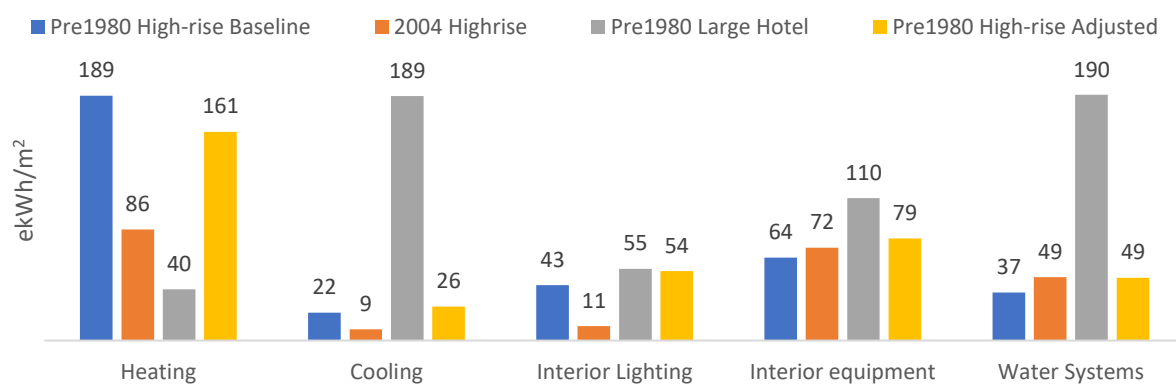


**Figure 36.** Adjusted post-1980 Midrise breakdown is most like the 2004 Highrise model

#### 6.1.4 Pre-1980 Highrise residence model adjustment

The pre-1980 Highrise *baseline* characterization template summarized in Section 5.3 was applied using the *Reference* method, resulting in a predicted EUI of 354kWh/m<sup>2</sup> for pre-1980 Highrise Residence buildings, which lies between the pre-1980 Large Hotel EUI (583kWh/m<sup>2</sup>) and the 2004 Highrise Apartment EUI (226kWh/m<sup>2</sup>).

End-use EUIs of the baseline pre-1980 Highrise, adjusted pre-1980 Highrise, pre-1980 Large Hotel and 2004 Highrise Apartment models are compared in Figure 37 while the overall EUI comparison is summarized in Figure 38. By reviewing the end-use results, it was determined that the most variation between the baseline residence model and the DOE models arose due to discrepancies in cooling, lighting, and water system energy consumption. The cooling EUI of the baseline model is 22kWh/m<sup>2</sup>, higher than the 9kWh/m<sup>2</sup> seen in the apartment model and much lower than the 189kWh/m<sup>2</sup> predicted with the hotel model. The difference in cooling EUI is due to the Highrise Apartment having a cooling COP of 3.4 while the Large Hotel has a cooling COP of 2.5. The Large Hotel model also has the largest equipment and lighting EUIs, which result in higher heat gains. Additionally, construction assemblies of DOE models were built to represent buildings of different time periods, resulting in different thermal efficiencies. The baseline lighting EUI consumption is 43kWh/m<sup>2</sup>, lower than the 55kWh/m<sup>2</sup> predicted by the hotel model and larger than the 11kWh/m<sup>2</sup> predicted by the apartment model. The baseline water system EUI consumption is 37kWh/m<sup>2</sup>, lower than the water system EUI predicted by the apartment model of 49kWh/m<sup>2</sup> and much lower than the 190kWh/m<sup>2</sup> predicted by the hotel model. In addition to this, the baseline equipment EUI is 13% and 72% lower than the apartment and large hotel models respectively.

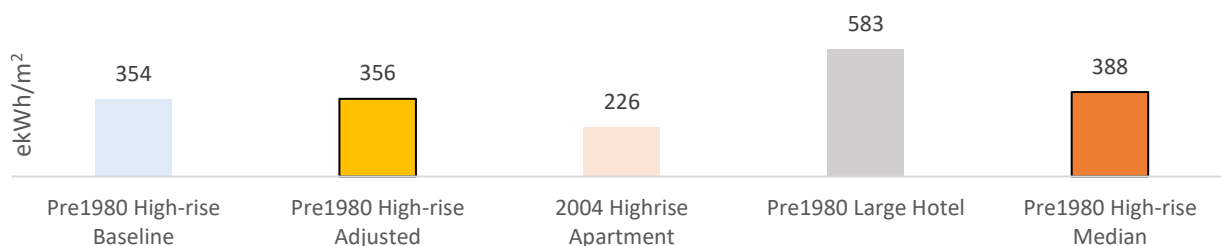


**Figure 37.** Comparison of the end-use EUIs predicted with reviewed DOE and developed residence models

To ensure that pre-1980 Highrise residences were predicting consumption with similar end use EUIs to those seen in DOE models, the following changes were done to the pre-1980 Highrise characterization template:

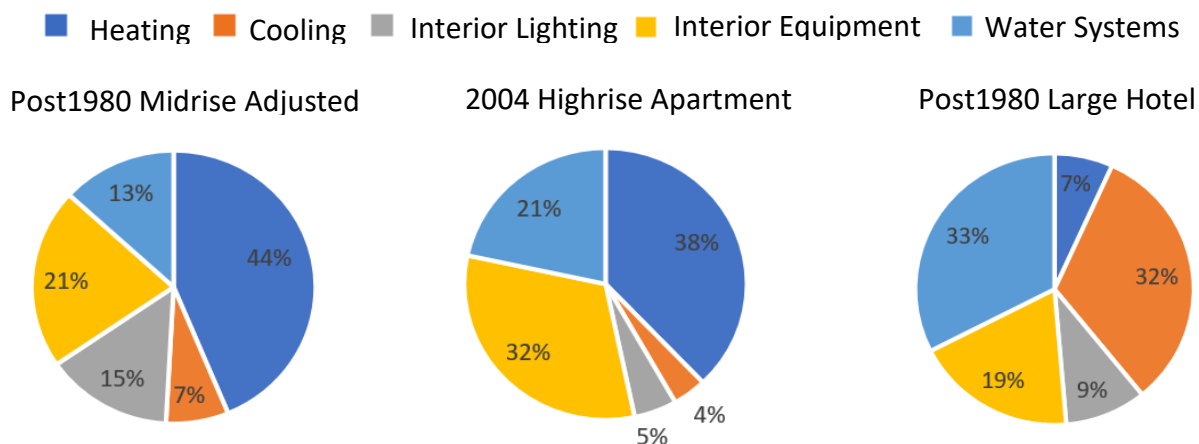
- Heating efficiency was increased from 0.78 to 0.83 as the initial efficiency produced significantly larger heating loads than both DOE models
- Lighting power density was increased from 12.72 W/m<sup>2</sup> to 16 W/m<sup>2</sup> to better represent the loads of the Large hotel
- Plug load density was increased from 14.6 W/m<sup>2</sup> to 18 W/m<sup>2</sup> as the initial load produced lower plug loads than both DOE models
- Hot water use was increased to 0.20 L/h/m<sup>2</sup> as selected rates were below both DOE models

These adjustments caused a 15% decrease in heating EUI, an 18% increase in cooling EUI, a 37% increase in lighting EUI, a 23% increase in equipment EUI, a 16% increase in hot water EUI and an increase of 9% in total EUI (Figure 38)



**Figure 38.-** The predicted EUI of the adjusted pre-1980 Highrise model is 9% lower than the EUI benchmark of the pre-1980 Highrise Category quantified at 388 ekWh/m<sup>2</sup>

Figure 39 reveals that the end-use breakdown predicted with the pre-1980 residence model is comparable to the end-use breakdown produced with the 2004 Highrise apartment model.



**Figure 39.** The adjusted pre-1980 Highrise predicted energy breakdown is most like the 2004 Highrise model

## 7 Energy Simulation Results

As noted previously, a cleaned dataset consisting of 20 student residence buildings in Southern Ontario has been used to identify necessary classification categories and features of each. These have been used to develop four energy modeling characterization templates to permit simulation using both *Wireframe* and *Reference* methods. This section presents simulation results and their comparison against measured 2013 Ontario MER data. Additionally, a random sampling study is presented which was considered to evaluate the performance of each method at different sample sizes.

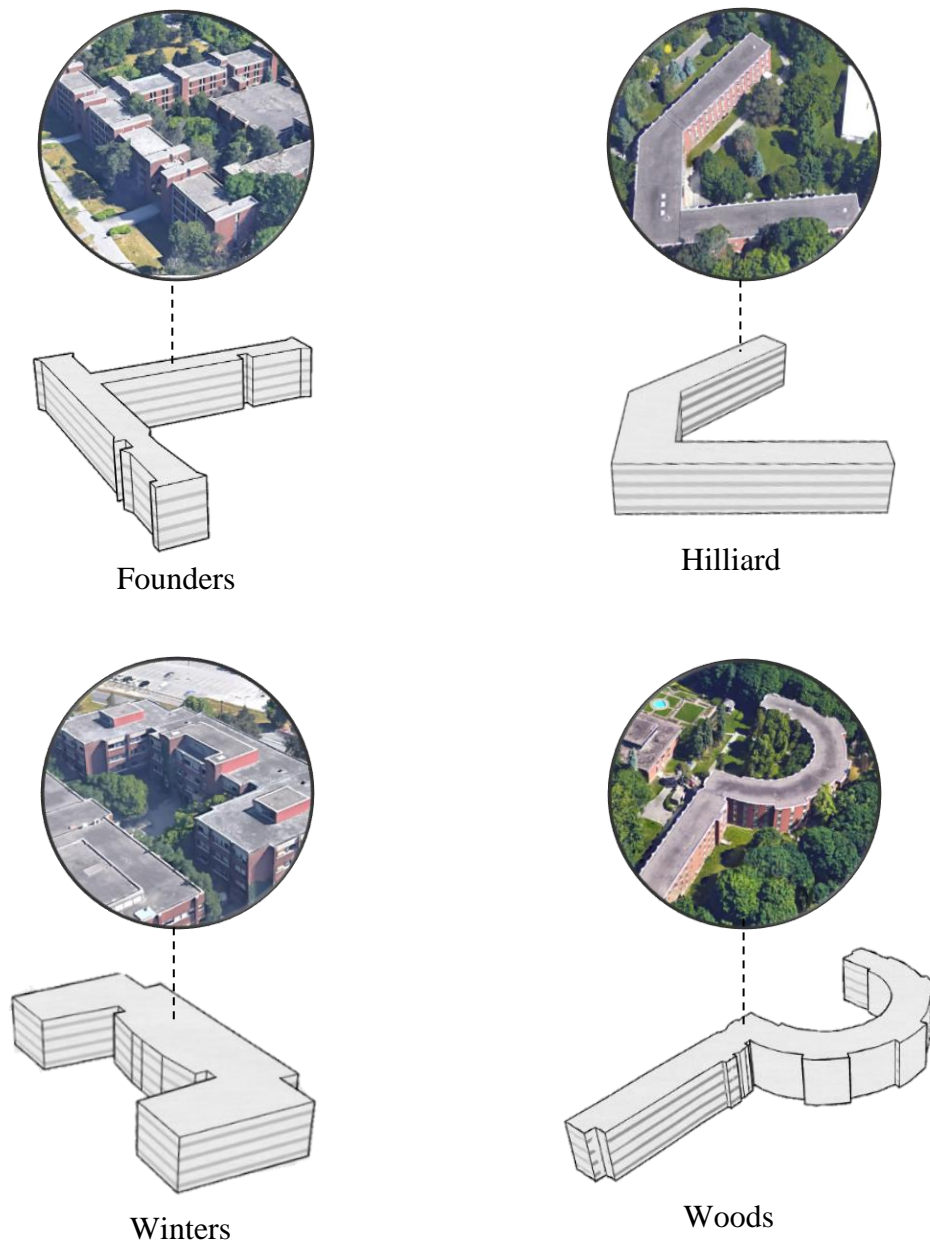
### 7.1 Comparison of Reference and Wireframe Predictions

This section presents the comparison of consumption predicted using the *Reference* and *Wireframe* methods to actual measured values. The comparison is done for each of the four previously defined categories: pre-1980 Lowrise, post-1980 Lowrise, post-1980 Midrise and pre-1980 Highrise. Results predicted by both methods for each category are compared to measured energy, heating, electricity and area to validate them. In addition, this section will present:

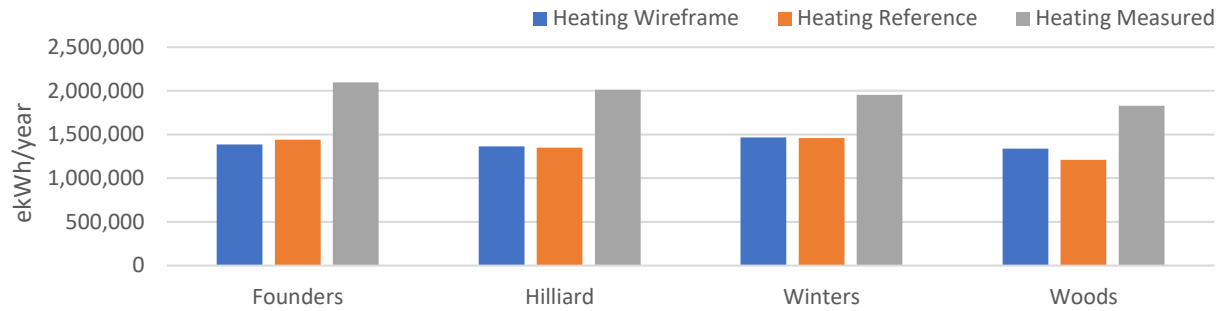
1. Aerial images of student residences considered in this study
2. *Wireframe* models developed to predict student residence consumption
3. End-use consumption predicted with *Wireframe* and *Reference* method

### 7.1.1 Pre-1980 Lowrise

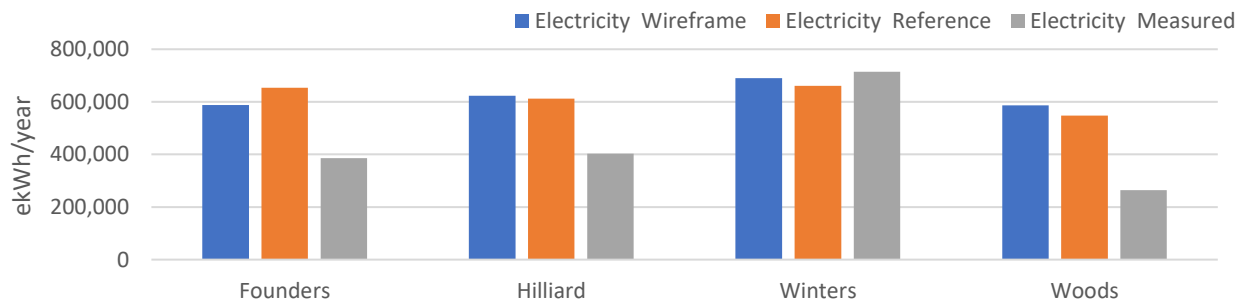
*Wireframe* models used to predict the consumption of pre-1980 Lowrise buildings are presented in Figure 40, while their simulated annual heating, electricity, energy, and area are presented in Figure 41 - 44.



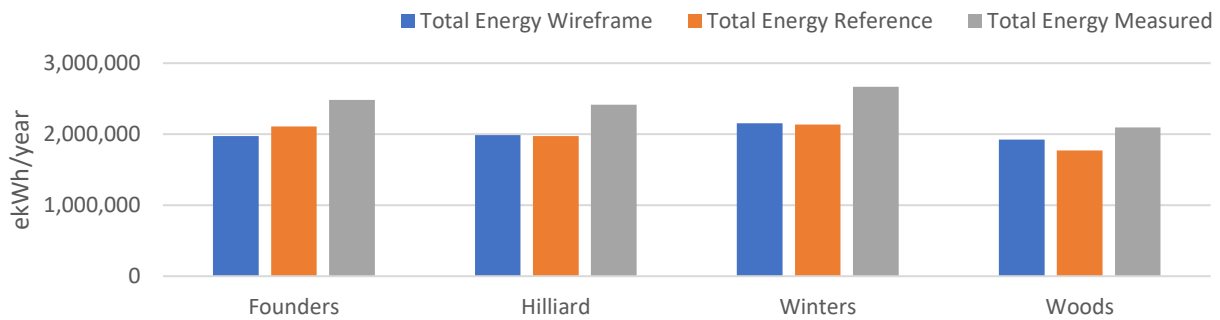
**Figure 40.** Building images and corresponding *Wireframe* method models for the pre-1980 Lowrise category



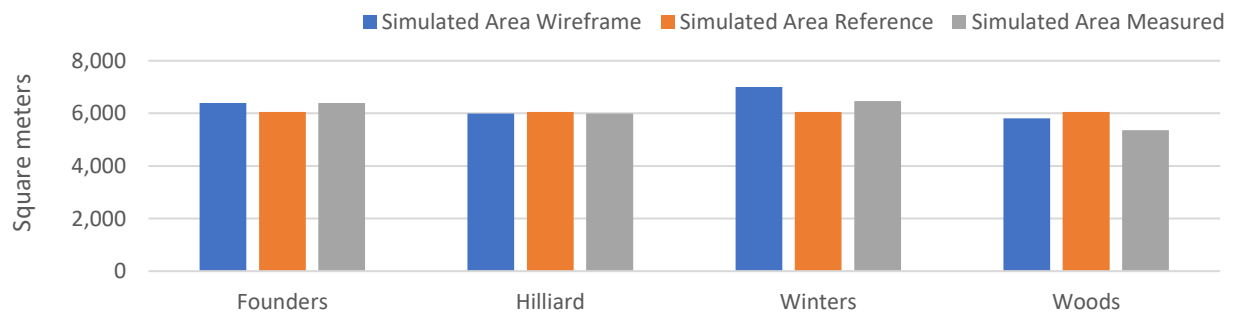
**Figure 41.** Pre-1980 Lowrise Heating comparison



**Figure 42.** Pre-1980 Lowrise Electricity comparison



**Figure 43.** Pre-1980 Lowrise Total Energy comparison



**Figure 44.** Pre-1980 Lowrise Area comparison. The simulated area for the Reference model does not change as the displayed area is the one used to predict the Reference EUI which is then scaled by multiplying by the measured area of the buildings.



Figure 41 compares the total heating consumption predicted by both methods to measured heating. Prediction errors for individual building heating ranges from -34% to -25% with the *Reference* method and -34% to -25% with the *Wireframe* method. In Figure 42, the total electricity predictions for both methods are compared to measured electricity. *Founders* and *Woods* are the residence models with highest electricity error predictions. These models reported measured electricity but no district cooling, while *Hilliard* and *Winters* reported measured electricity and district cooling. All four residences belong to the same university, so it is suspicious that the two models that did not report district cooling (*Founders* and *Woods*) are also the models with highest errors. Errors for electricity predictions range from -4% to 122% with the *Wireframe* method and -8% to 107% with the *Reference* method. These are the highest range of predicted errors for this sample. Figure 43 compares the total energy consumption predicted by both methods to measured energy. Errors for energy predictions go from -21% to -8% with the *Wireframe* method and -20% to -15% with the *Reference* method. In Figure 44, areas used to predict consumption are compared to measured residence areas. *Winters Wireframe* model had the largest error as it uses an area 15% larger than what was measured. The area used for *Wireframe* predictions has a 0% to 8% error range, while the area used for *Reference* predictions has a -6% to 13% error range.

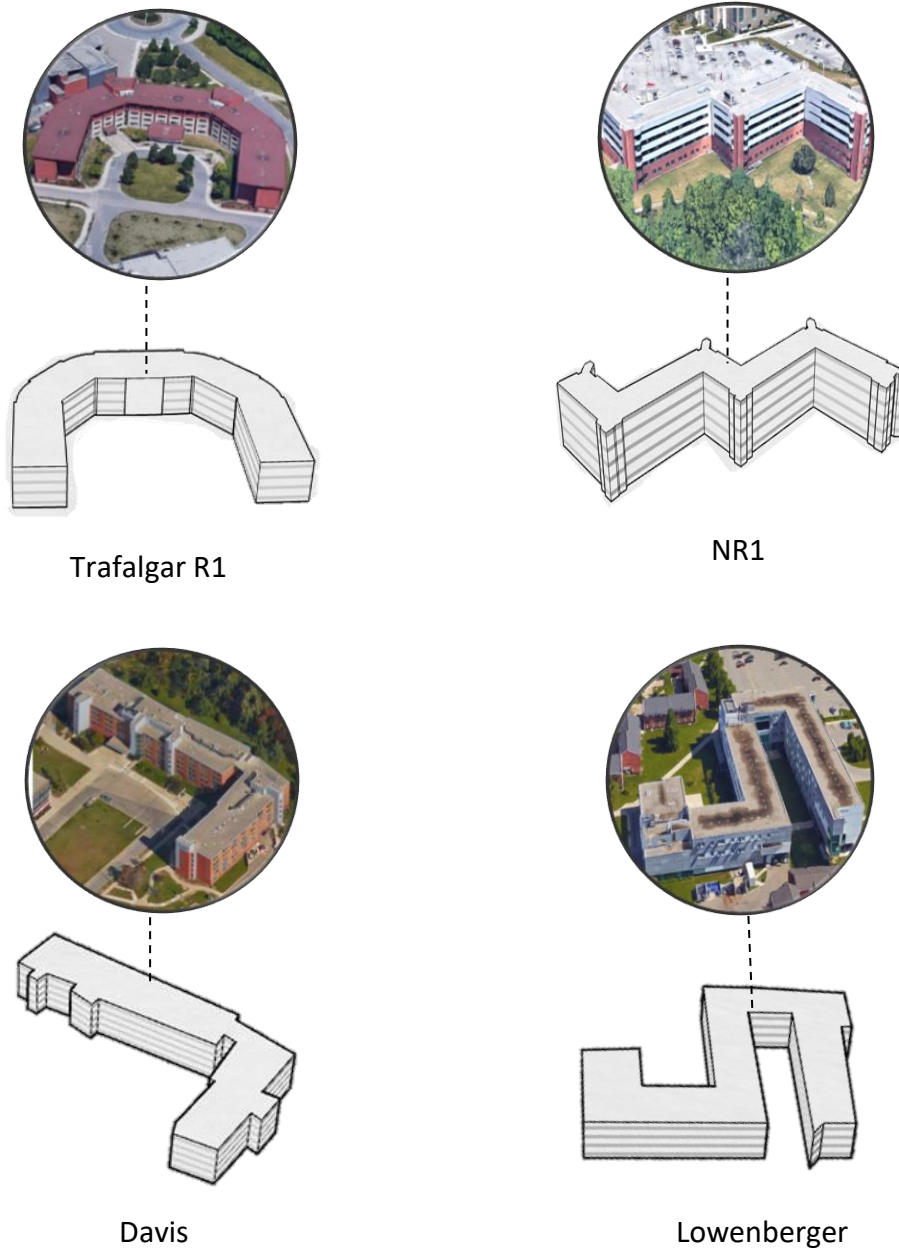
Table 34 summarizes the pre-1980 Lowrise individual building percentage error ranges. Note that *Reference* method area errors are obtained by comparing the *Reference* model area to measured areas.

**Table 34.** Percentage error ranges for pre-1980 Lowrise buildings

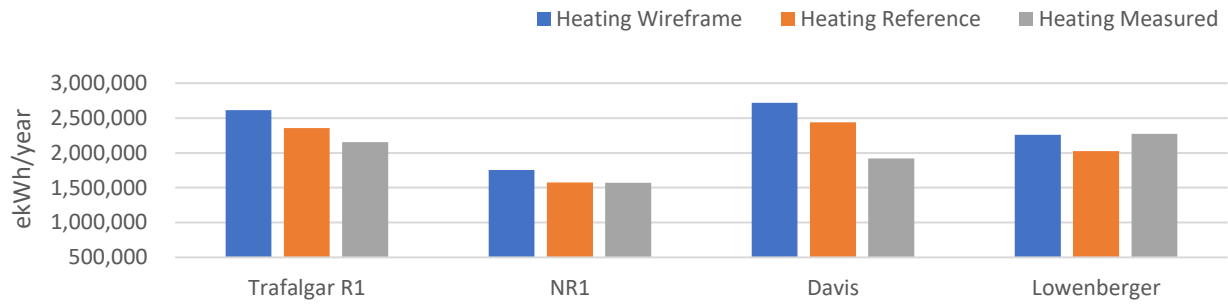
	Wireframe			Reference		
Heating	-34%	to	-25%	-34%	to	-25%
Electricity	-4%	to	122%	-8%	to	107%
Energy	-21%	to	-8%	-20%	to	-15%
Area	0%	to	8%	-6%	to	13%

### 7.1.2 Post-1980 Lowrise

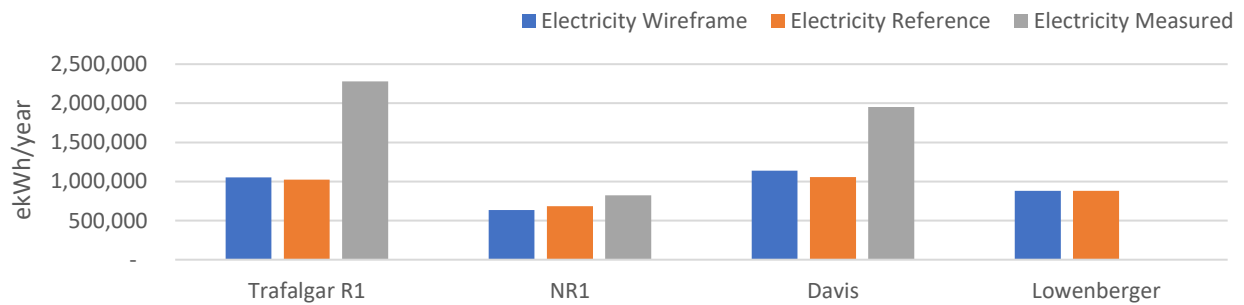
*Wireframe* models used to predict the consumption of post-1980 Lowrise buildings are presented in Figure 45, while their simulated annual heating, electricity, energy, and area are presented in Figures 46 – 49.



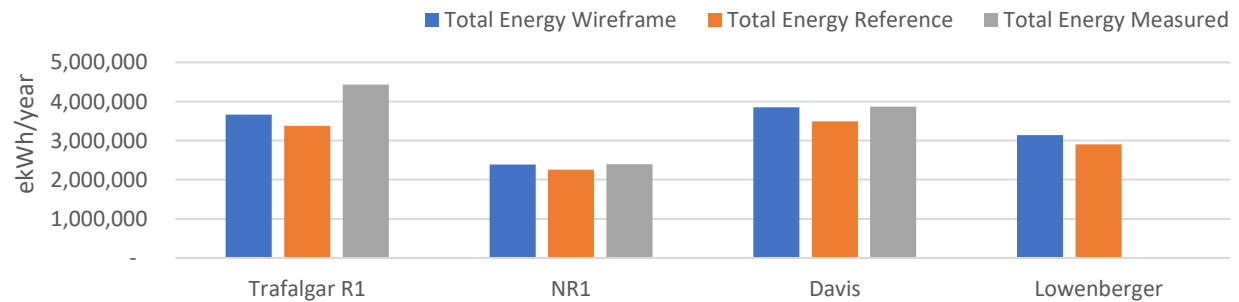
**Figure 45.** Building images and corresponding Wireframe method models for the post-1980 Lowrise category



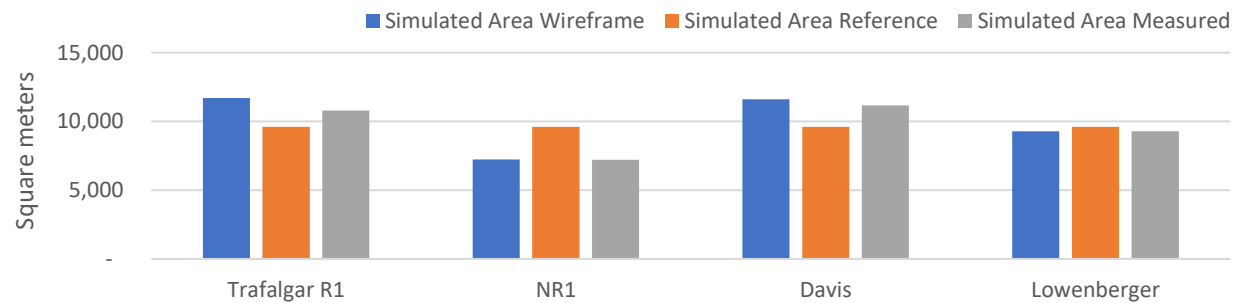
**Figure 46.** Post-1980 Lowrise Heating comparison



**Figure 47.** Post-1980 Lowrise Electricity comparison



**Figure 48.** Post-1980 Lowrise Total Energy comparison



**Figure 49.** Post-1980 Lowrise Area comparison

Figure 46 compares the total heating consumption predicted by both methods to measured heating. Prediction errors for individual building heating ranges from -11% to 27% with the *Reference* method and -1% to 42% with the *Wireframe* method. In Figure 47, the total electricity predicted by both methods are compared to measured electricity. *Lowenberger* has no reported measured consumption so only predicted consumption values are compared. Predictions errors for individual building electricity ranges from -55% to -17% with the *Reference* method and -54% to -23% with the *Wireframe* method. Figure 48 compares the total energy consumption predicted by both methods to measured energy. Measured energy reported for *Lowenberger* was ignored as it had the same value reported for heating consumption. Predictions errors for individual building total energy ranges from -17% to 0% with the *Wireframe* method and -24% to -6% with the *Reference* method. In Figure 49 areas used to predict consumption are compared to measured areas. In most models, the area used for *Wireframe* predictions were more like measured values. The area used for *Wireframe* predictions has a 0% to 8% error range, while the area used for *Reference* predictions has a -14% to 33% error range.

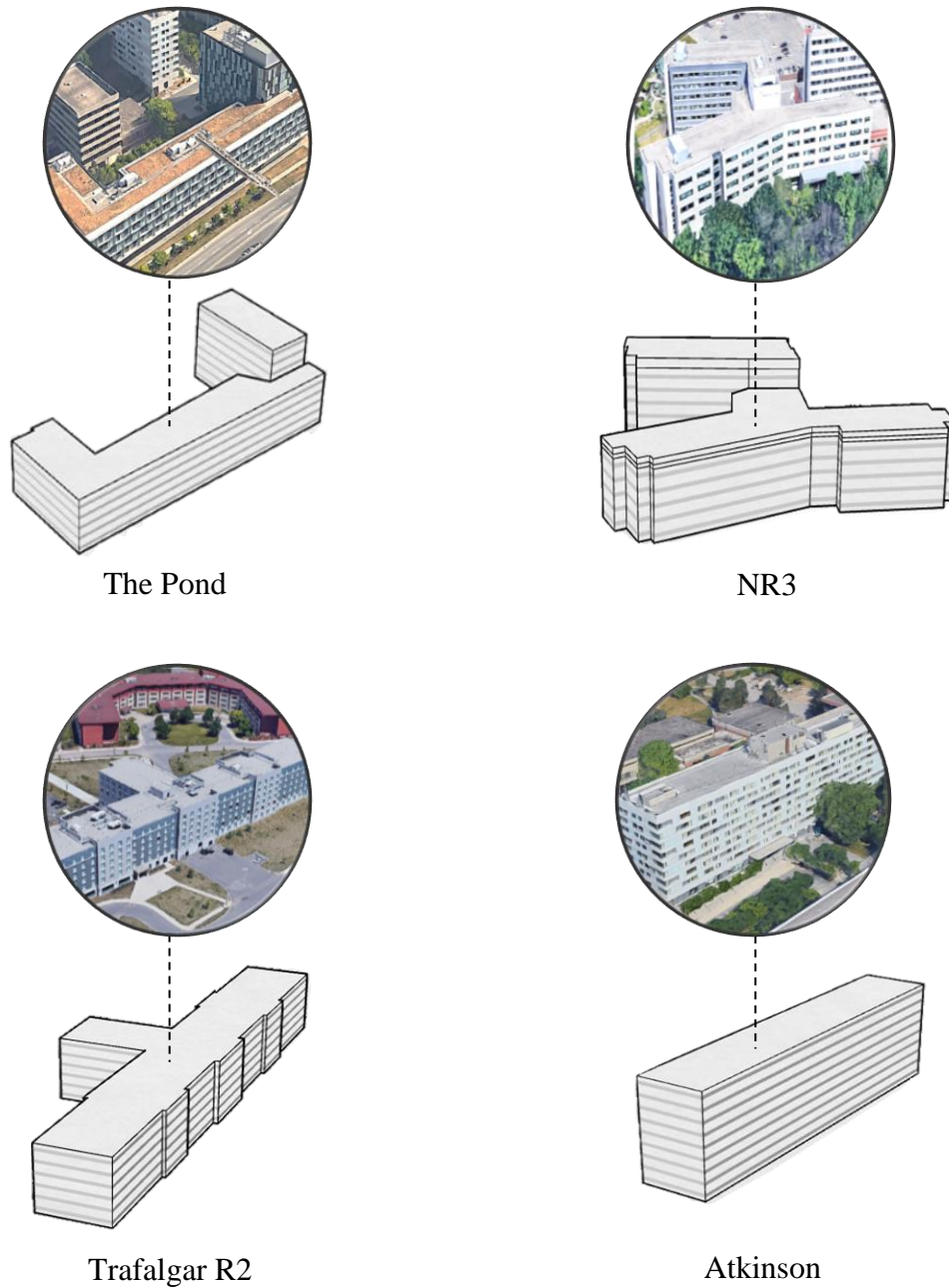
Table 35 summarizes post-1980 Lowrise individual building percentage error ranges. Note that *Reference* method area errors are obtained by comparing the *Reference* model area to measured areas.

**Table 35.** Percentage error ranges for post-1980 Lowrise buildings

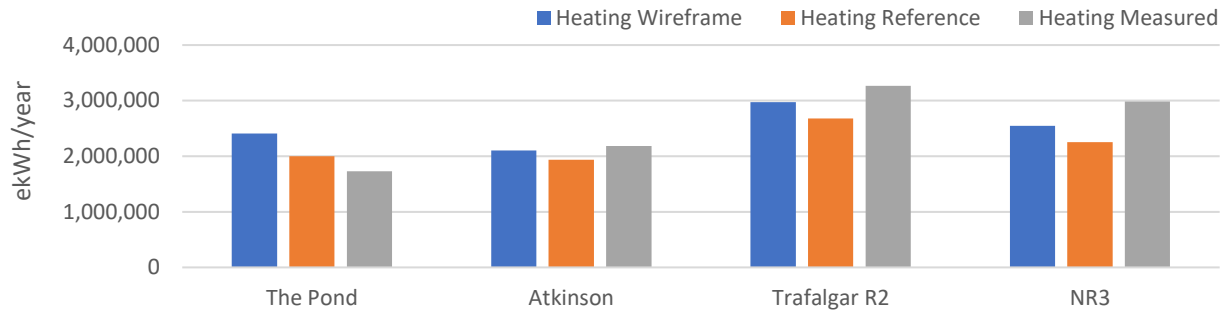
	Wireframe			Reference		
Heating	-1%	to	42%	-11%	to	27%
Electricity	-54%	to	-23%	-55%	to	-17%
Energy	-17%	to	0%	-24%	to	-6%
Area	0%	to	8%	-14%	to	33%

### 7.1.3 Post-1980 Midrise

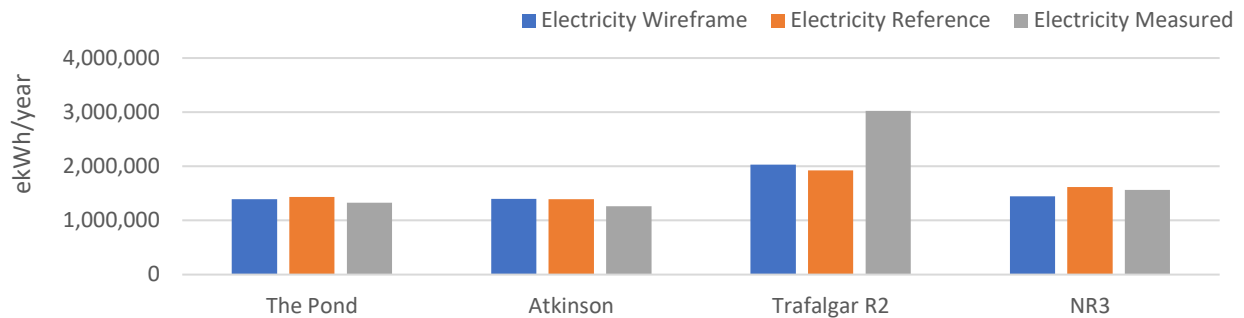
*Wireframe* models used to predict the consumption of post-1980 Midrise buildings are presented in Figure 50, while their simulated annual heating, electricity, energy, and area are presented in Figures 51 - 54.



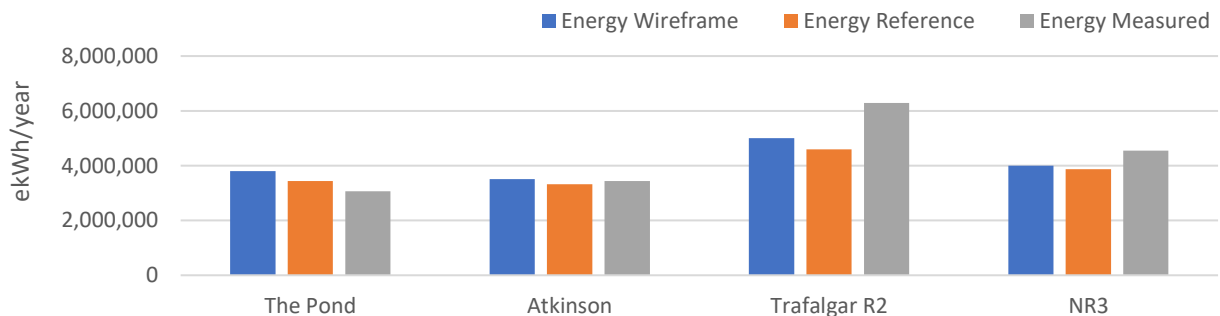
**Figure 50.** Building images and corresponding *Wireframe* method models for the post-1980 Midrise category



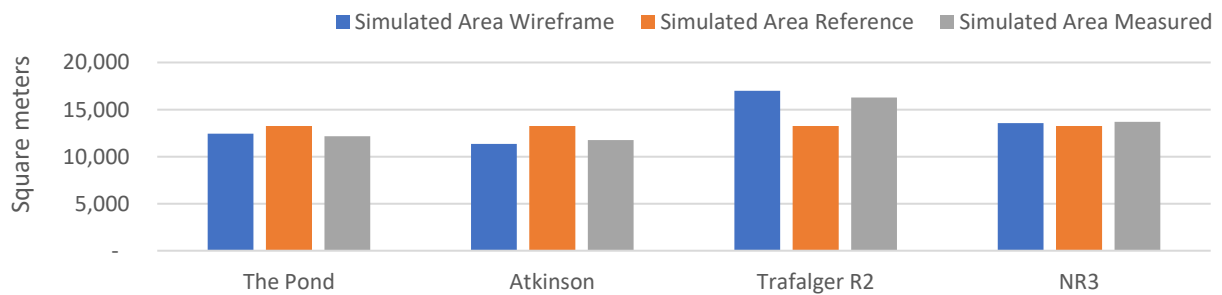
**Figure 51.** Post-1980 Midrise Heating comparison



**Figure 52.** Post-1980 Midrise Electricity comparison



**Figure 53.** Post-1980 Midrise Total Energy comparison



**Figure 54.** Post-1980 Midrise Area comparison

Figure 51 compares the total heating predicted by both methods to measured heating consumption. Predictions errors for individual building heating ranges from -24% to 15% with the *Reference* method and -15% to 39% with the *Wireframe* method. The error seen with the *Wireframe* method is partially due to how the *Pond Residence* was modelled, this will be discussed in greater detail in the Discussion section of this thesis. In Figure 52, the total electricity predicted by both methods are compared to measured electricity. In this sample, electricity predictions are similar to measured consumption, except for the *Trafalgar R2* model, where measured loads are at least 33% higher than those predicted with either method. Predictions errors for individual building electricity ranges from -36% to 10% with the *Reference* method and -33% to 11% with the *Wireframe* method. Figure 53 compares the total energy consumption predicted by both methods to measured energy. The models with most variation between the *Wireframe* and *Reference* method predictions are *The Pond* and *Trafalgar R2*. Predictions errors for individual building total energy ranges from -27% to 12% with the *Reference* method and -20% to 24% with the *Wireframe* method. In Figure 54, areas used to predict consumption are compared to measured areas. The area used for *Wireframe* predictions have a -4% to 4% error range, while the area used for *Reference* predictions has a -19% to 13% error range.

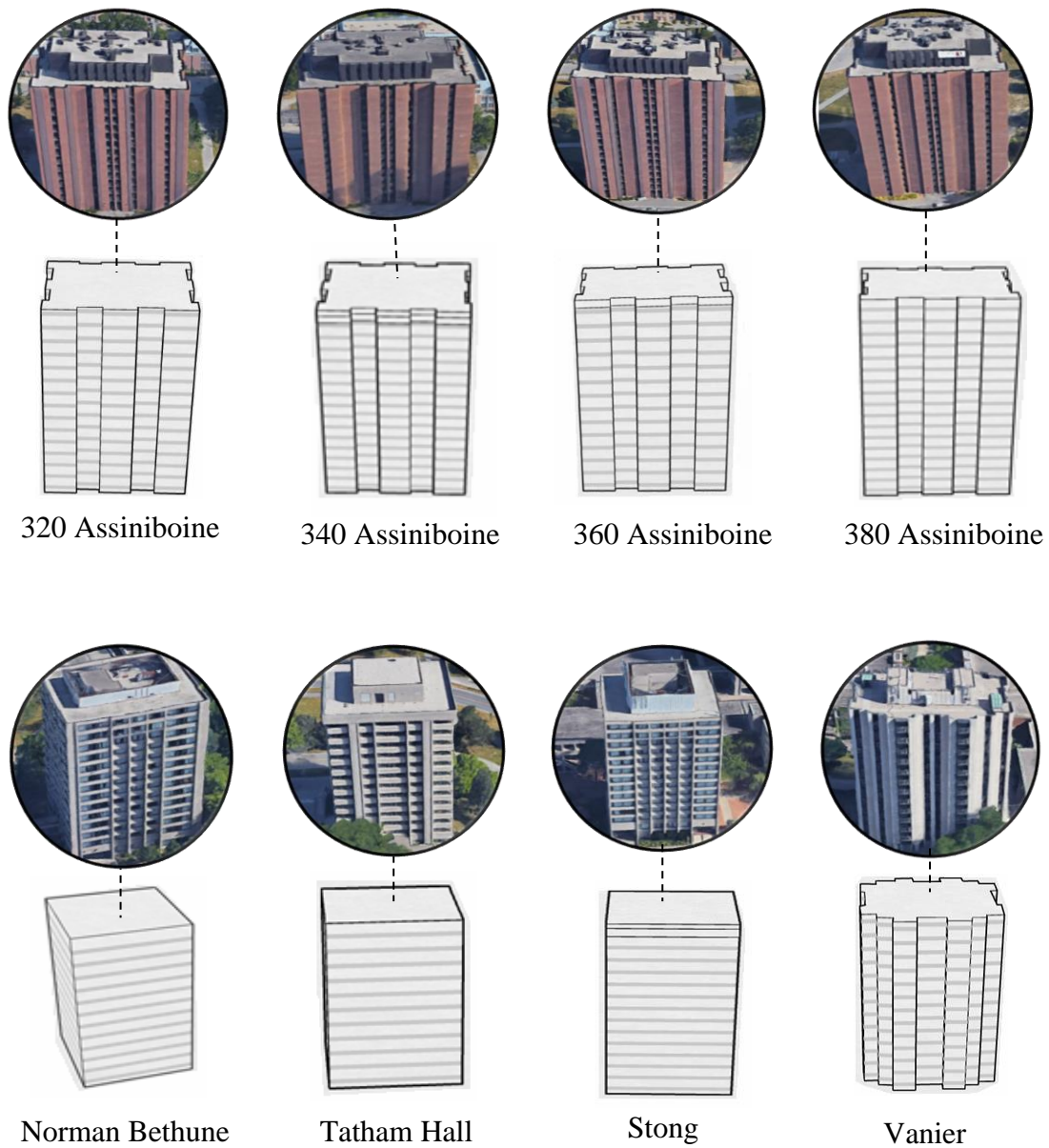
Table 36 summarizes post-1980 Midrise individual building percentage error ranges. Note that *Reference* method area errors are obtained by comparing the *Reference* model area to measured areas.

**Table 36.** Percentage error ranges for post-1980 Midrise buildings

	Wireframe			Reference		
Heating	-15%	to	39%	-24%	to	15%
Electricity	-33%	to	11%	-36%	to	10%
Energy	-20%	to	24%	-27%	to	12%
Area	-4%	to	4%	-19%	to	13%

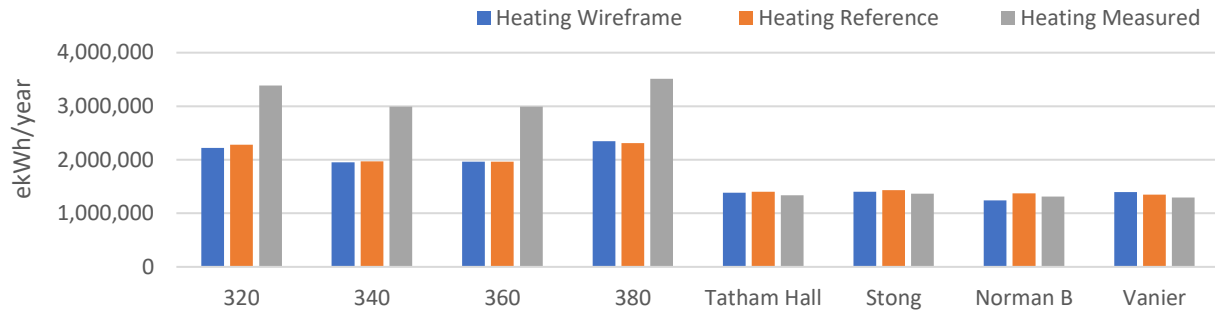
#### 7.1.4 Pre-1980 Highrise

*Wireframe* models used to predict the consumption of pre-1980 Highrise buildings are presented in Figure 55, while their simulated annual heating, electricity, energy, and area are presented in Figure 56 - 59.

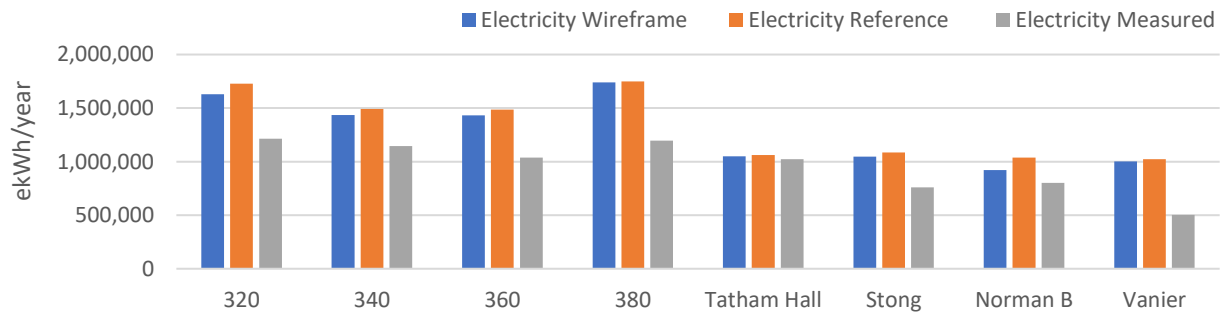


**Figure 55.** Building images and corresponding *Wireframe* method models for the pre-1980 Highrise category

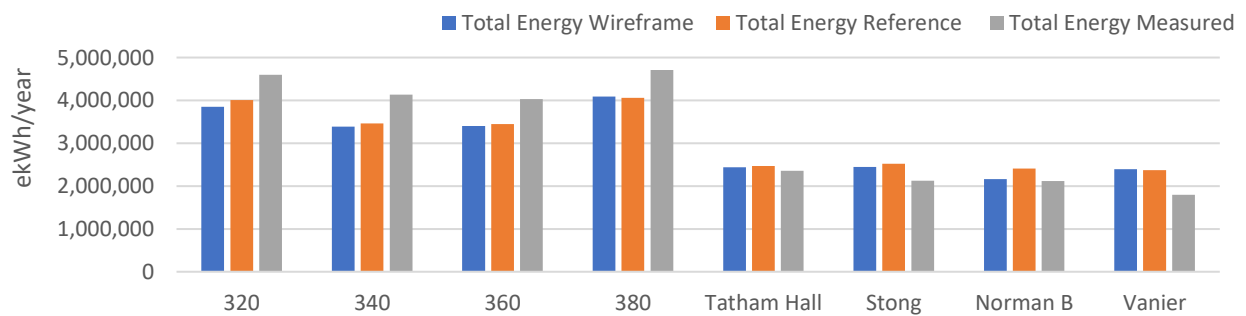




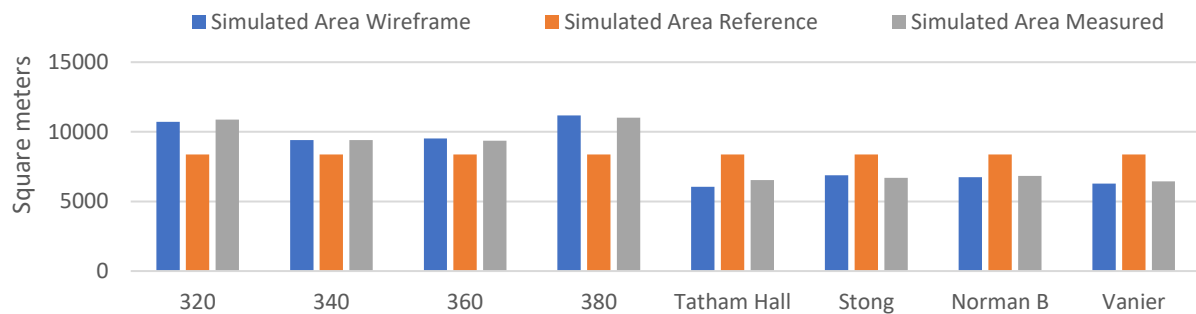
**Figure 56.** Pre-1980 Highrise Heating comparison



**Figure 57.** Pre-1980 Highrise Electricity comparison



**Figure 58.** Pre-1980 Highrise Total Energy comparison



**Figure 59.** Pre-1980 Highrise Area comparison

Figure 56 compares the total heating consumption predicted by both methods to measured heating. Not much variation is seen between heating predictions from either method. Predictions errors for individual building heating ranges from -34% to 5% with the *Reference* method and -35% to 8% with the *Wireframe* method. In Figure 57, the total electricity predicted by both methods are compared to measured electricity. In most residences, the *Wireframe* method predicted more accurate electricity consumption, however, the differences are relatively small. The less complex models (Norman Bethune, Tatham Hall and Stong) appear to be better at predicting consumption when compared to buildings that have more complex geometry (320, 340, 360, 380, and Vanier). Predictions errors for individual building electricity ranges from 4% to 104% with the *Reference* method and 3% to 99% with the *Wireframe* method. Figure 58 compares the total energy consumption predicted by both methods to measured energy. Not much variation is seen between the consumption predicted with either method. In this sample, *Reference* method models appear to predict total energy consumption with greater accuracy. Predictions errors for individual building total energy ranges from -16% to 32% with the *Reference* method and -18% to 33% with the *Wireframe* method. In Figure 59, areas used to predict consumption are compared to measured areas. The area used for *Wireframe* predictions had a -7% to 3% error range, while the area used for *Reference* predictions had a -24% to 30% error range.

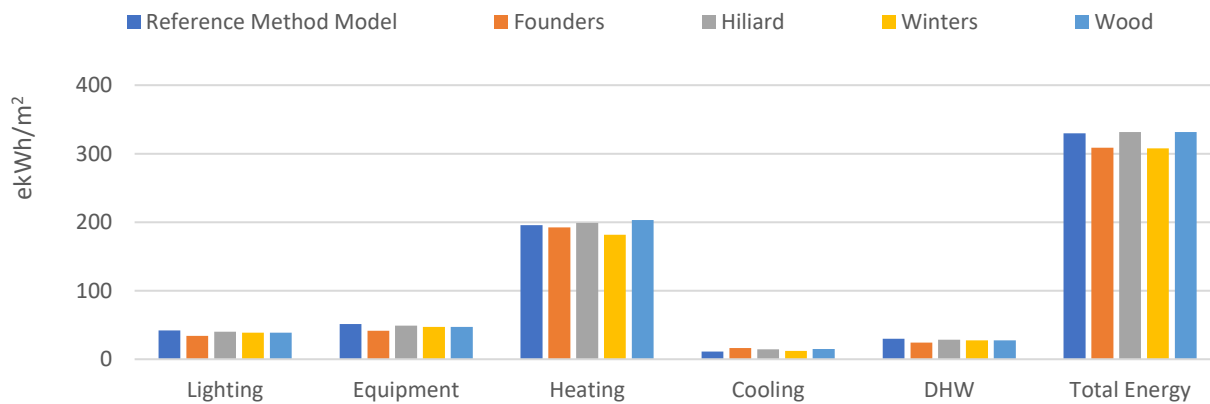
Table 37 summarizes pre-1980 Highrise individual building percentage error ranges. Note that *Reference* method area errors are obtained by comparing the *Reference* model area to measured areas.

**Table 37.** Percentage Error ranges for pre-1980 Highrise buildings

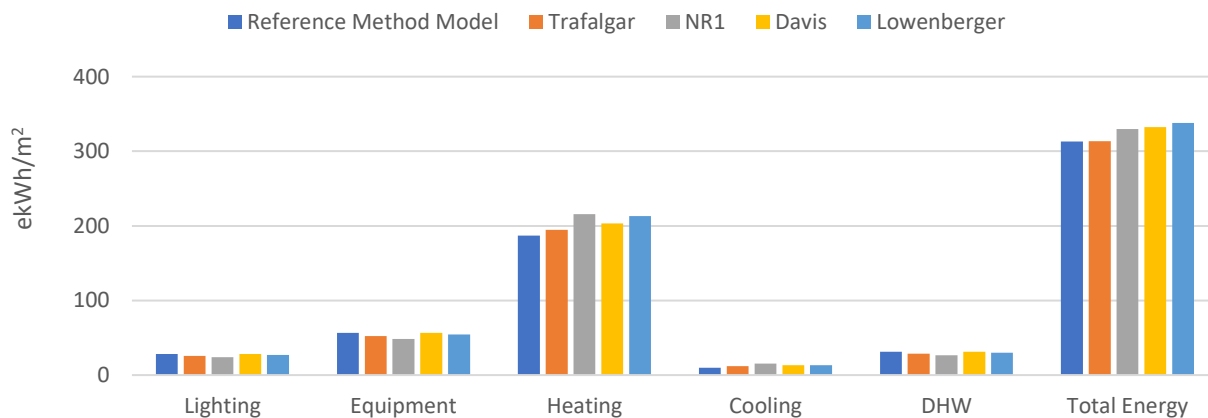
	Wireframe			Reference		
Heating	-35%	to	8%	-34%	to	5%
Electricity	3%	to	99%	4%	to	104%
Energy	-18%	to	33%	-16%	to	32%
Area	-7%	to	3%	-24%	to	30%

## 7.2 End-use energy by building

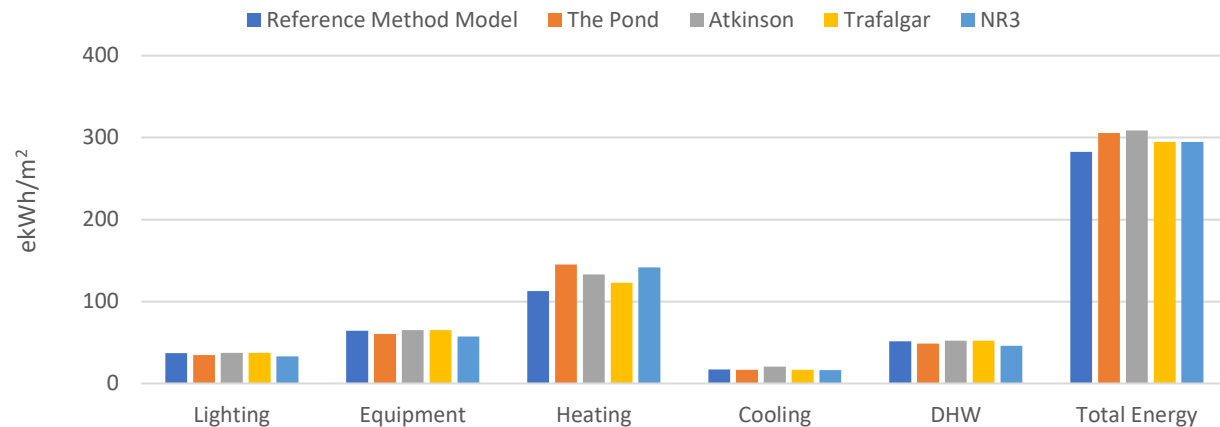
The end-use EUI predicted for student residences using *Reference* and *Wireframe* methods are compared in Figure 60- Figure 63. These figures present the end-use consumption predicted for each of the four previously defined categories. End-use intensities are compared by category provide insight regarding differences between prediction methods. Understanding what causes consumption differences allows identification of when buildings are better represented with the *Wireframe* method and where buildings will be equally represented with either bottom-up method.



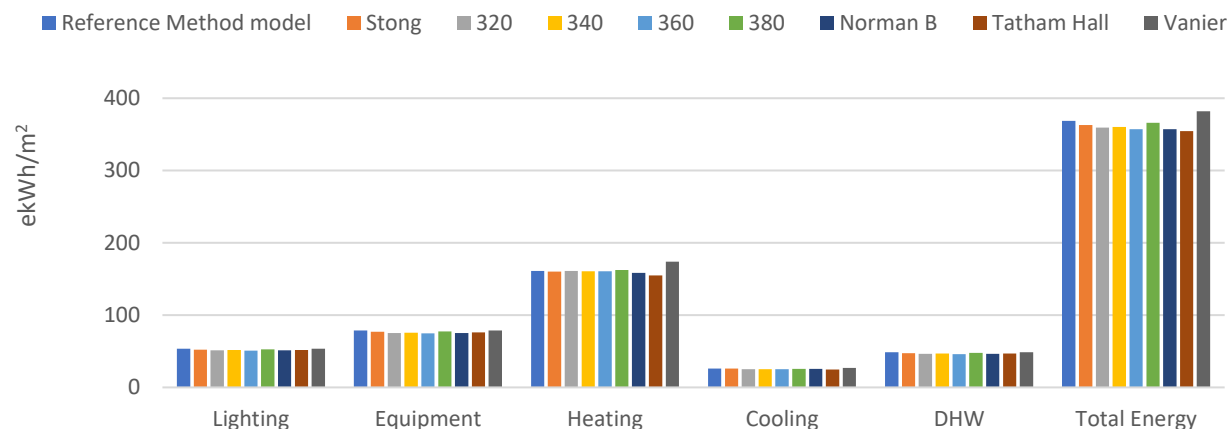
**Figure 60.** Pre-1980 Lowrise predicted energy end-use by building



**Figure 61.** Post-1980 Lowrise predicted energy end-use by building



**Figure 62.** Post-1980 Midrise predicted energy end-use by building



**Figure 63.** Pre-1980 Highrise predicted energy end-use by building

Building categories with least aggregate total energy variation between *Reference* and *Wireframe* predictions are the pre-1980 Lowrise (Figure 60; 1%) and the pre-1980 Highrise (Figure 63; 2%). Building categories with most consumption variation are the post-1980 Lowrise (Figure 61; 7%) and the post-1980 Midrise (Figure 62; 7%). Post-1980 models also presented highest error between measured areas and *Reference* model areas used to predict their EUI. This suggests that further dividing post-1980 categories by area size might decrease these errors, highlighting the importance of classifying the building stock by area. Not much variation is seen between the methods, if any, it is seen in conditioning end-uses, suggesting that these variations are related to the form of the models.

## 7.3 Error Analysis

### 7.3.1 Pre-1980 Lowrise

The comparison between *Wireframe* and *Reference* method prediction accuracies for the pre-1980 Lowrise category is summarized in Table 38. Percentage error represents the accuracy of the models to predict the aggregate consumption of the sample while RMSE represents the sample standard deviation of the differences between predicted and measured values of the sample.

**Table 38.** Percentage error and RMSE of pre-1980 Lowrise buildings

	Percentage Error (%)		RMSE (%)	
	Wireframe	Reference	Wireframe	Reference
Heating	-30%	-31%	30%	31%
Electricity	41%	40%	72%	69%
Energy	-17%	-17%	21%	26%
Area	4%	0%	6%	8%

It is evident from this table that the *Wireframe* and *Reference* methods have very similar prediction accuracy. For example, when reviewing the aggregate heating consumption, the *Wireframe* method underpredicted by 30%, while the *Reference* method under-predicted heating by 31%. The RMSE of heating consumption is also very similar for both methods, 30% for the *Wireframe* and 31% for the *Reference* method. This means that both methods are as accurate at predicting heating consumption. The aggregate electricity predicted by both methods are over by 41% with the *Wireframe* and 40% with the *Reference* method, poor results but consistent with the accuracies of the methods being similar. The RMSE of predicted electricity shows that the *Reference* method (69%) is slightly better than the *Wireframe* (72%). As it was noted earlier, this error in electricity could be due to improper energy data reporting. The two buildings that had highest electricity prediction errors did not report cooling energy while others from this sample did, even though they are part of the same university. The other explanation for this error is that characterization templates of these models assume more energy inefficient appliances and lighting systems than what is used in these buildings. This over-prediction of electricity use might be responsible for the under-prediction of heating, as heating loads are influenced by internal gains caused by lighting and electric equipment. The percentage error of total energy is equal for both methods (-17%) while the RMSE of total energy predicted with the *Wireframe* method being slightly better.

### 7.3.2 Post-1980 Lowrise

The comparison between *Wireframe* and *Reference* method prediction accuracies for the post-1980 Lowrise category is summarized in Table 39.

**Table 39.** Percentage Error and RMSE of post-1980 Lowrise buildings

	Percentage Error (%)		RMSE (%)	
	Wireframe	Reference	Wireframe	Reference
Heating	18%	6%	24%	15%
Electricity	-44%	-45%	42%	43%
Energy	-7%	-15%	10%	15%
Area	4%	0%	5%	19%

It is evident from this table that for aggregate energy, the *Wireframe* method has noticeably better prediction accuracy than the *Reference* method. For example, the *Wireframe* method under-predicted total energy consumption by 7%, while the *Reference* method under-predicted consumption by 15%. The RMSE of predicted energy shows that for individual building prediction the *Wireframe* method (10%) is slightly better than the *Reference* (15%), but both with credible values. The *Wireframe* method used 4% more area than what was measured to predict consumption. This results in more energy being predicted as more space is considered. The difference in predicted energy between the *Wireframe* and *Reference* method could be due to the additional area considered. When reviewing aggregate heating predictions, the *Reference* method predicted consumption 6% above what was measured, much better than the 18% over-predicted with the *Wireframe* method. Heating RMSE support these results, however, with greater variation. The difference between the *Reference* and *Wireframe* heating predictions are likely related to the form of the buildings. Aggregate electricity predictions were also compared, both the *Wireframe* (-44%) and *Reference* (-45%) methods were extremely poor, likely due to defined equipment and lighting efficiencies. Equipment and lighting efficiencies come from post-1980 DOE reference models and not from audits performed on these buildings. It is possible that more energy inefficient appliances, lighting, and equipment are used in these buildings. The under-prediction of electricity use might be partially responsible for the over-prediction of heating, as heating loads are influenced by internal gains caused by lighting and electric equipment.

### 7.3.3 Post-1980 Midrise

Table 40 presents the Percentage Error and Root Mean Square Error of post-1980 Lowrise buildings.

**Table 40.** Percentage error and RMSE of post-1980 Midrise buildings

	Percentage Error (%)		RMSE (%)	
	Wireframe	Reference	Wireframe	Reference
Heating	-1%	-13%	21%	18%
Electricity	-13%	-11%	18%	19%
Energy	-6%	-12%	17%	17%
Area	1%	-2%	3%	12%

It is evident from this table that for aggregate energy, the *Wireframe* method has noticeably better prediction accuracy than the *Reference* method. For example, the *Wireframe* method under-predicted total energy consumption by 6%, while the *Reference* method under-predicted consumption by 12%. The RMSE of predicted energy is 17%, suggesting that for individual building consumption both methods predict energy with the same accuracy. When reviewing heating predictions, the *Wireframe* method under-predicted consumption by 1% of what was measured, much better than the 13% under-predicted with the *Reference* method. Heating RMSE suggests that *Wireframe* models have greater error variation when predicting individual building heating consumption. The 18% percentage error difference between the *Reference* and *Wireframe* heating predictions is partially due to the form of the buildings. Electricity predictions of both the *Wireframe* (-13%) and *Reference* (-11%) methods were good. Equipment and lighting efficiencies come from post-1980 DOE reference models and not from audits performed on these buildings, so some variation is expected. In this sample, the percentage error of the *Reference* area is off by 2%. This means that the model developed to represent post-1980 Midrise *Reference* models was 2% below the area mean of the sample. This is simply a modeling issue; however, this does not affect significantly the results as the EUI of the *Reference* model is then multiplied by measured areas.

### 7.3.4 Pre-1980 Highrise

The comparison between *Wireframe* and *Reference* method prediction accuracies for the pre-1980 Highrise category is summarized in Table 41.

**Table 41.** Percentage error and RMSE of pre-1980 Highrise buildings

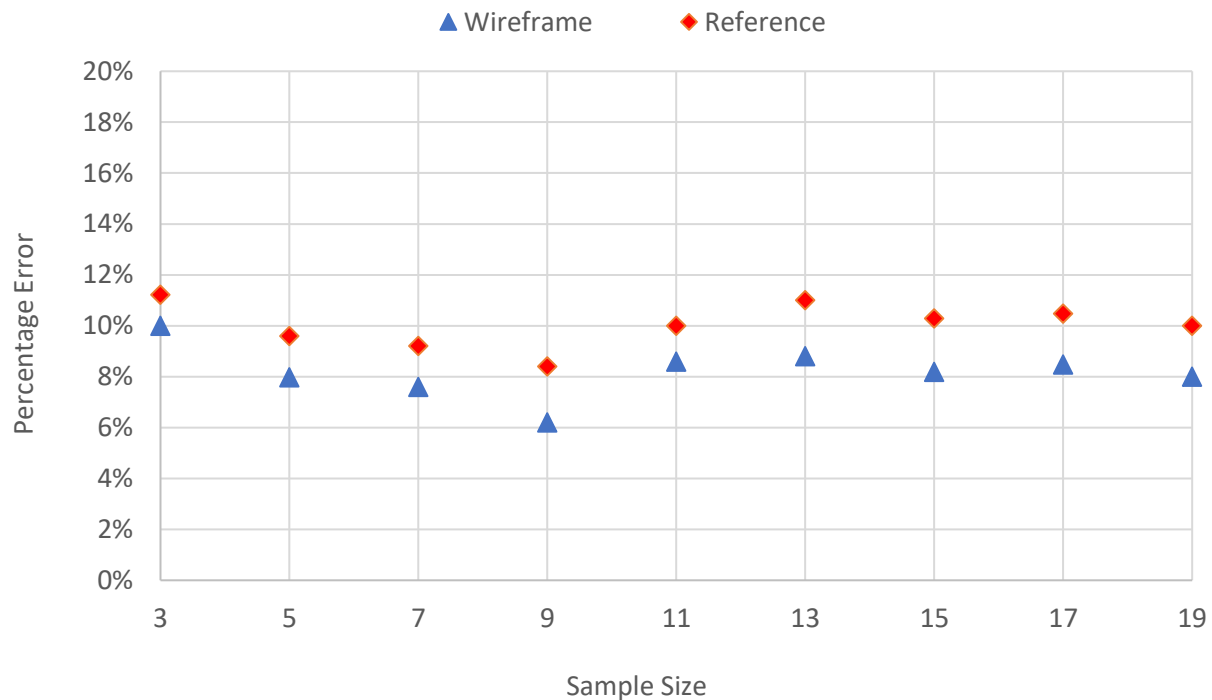
	Percentage Error (%)		RMSE (%)	
	Wireframe	Reference	Wireframe	Reference
Heating	-24%	-23%	24%	24%
Electricity	34%	39%	46%	50%
Energy	-7%	-4%	17.2%	17.3%
Area	-1%	0%	3%	23%

It is evident from this table that for aggregate energy, the *Reference* method has slightly better prediction accuracy than the *Wireframe* method. For example, the *Wireframe* method under-predicted consumption by 7% while the *Reference* method under-predicted consumption by 4%. The RMSE values show no significant variation (0.1%) between the methods. Suggesting that both methods predict consumption with similar accuracy even when comparing individual building consumption. The *Wireframe* method used 1% less area to predict consumption than what was measured. The difference in predicted energy between the methods is partially due to the *Wireframe* method using less area to predict consumption while the *Reference* method considers that which was measured. Electricity predictions of both the *Wireframe* (34%) and *Reference* (39%) methods were poor, likely due to defined equipment and lighting efficiencies. Equipment and lighting efficiencies come from pre-1980 DOE reference models and not from audits performed on these buildings. It is possible that more energy efficient appliances, lighting and equipment are used in these buildings. Having inefficient appliances and lighting systems increase internal heat gains, which in turn decreases heating energy. Suggesting once again that the over-prediction of electricity use being partially responsible for the under-prediction of heating, as heating loads are influenced by internal gains caused by lighting and electric equipment.



### 7.3.5 Random Sampling

To further explore the merits of the *Reference* and *Wireframe* methods, final building results were imported into a database and randomly sampled (20 times) without replacement to generate building subsets of varying sizes ( $n=3,5,7,9,11,13,15,17$  and  $19$ ) with replacement between subset generation. The predicted annual total energy of each building was then totaled for each subset and compared with actual totals for the same buildings. The average total energy error rate is plotted against sample size for each method in Figure 64.



**Figure 64.** Average total energy error rate against sample size.

As seen in Figure 64, the error rates between the *Wireframe* and *Reference* methods do not seem to vary significantly with different sample sizes. Smaller samples seem to have more variation with error than larger sample sizes where the error finds a plateau state. In all samples the *Reference* method has a higher error, however the methods differ by less than 2%, which raise questions as to the cost-benefit of accurately modeling the building's geometry and orientation as required in the *Wireframe Method*.

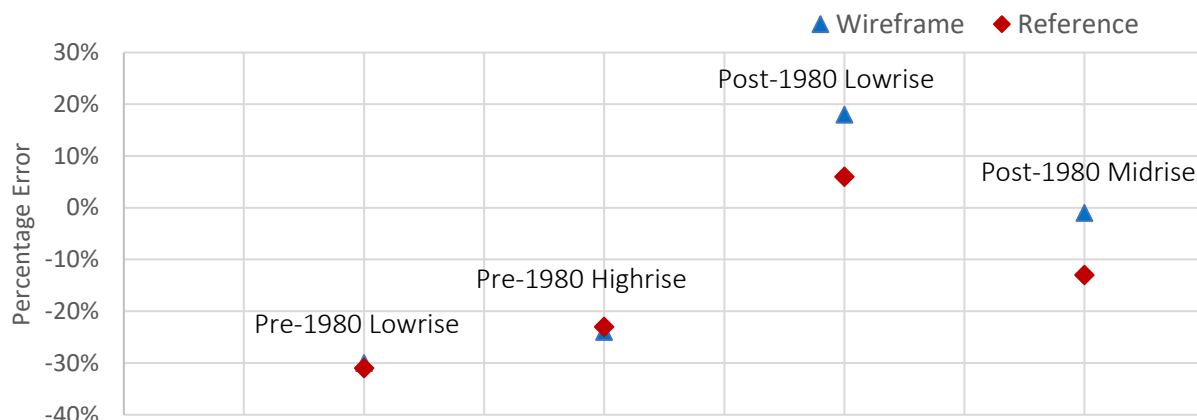
## 8 Discussion

The findings of this study suggest that both the *Reference* and *Wireframe* methods can predict consumption with similar accuracy, including buildings which display high geometric complexity and low thermal resistivity envelopes. While the *Wireframe* method models tended to predict more heating energy usage than *Reference* method models, this difference is not substantial, particularly considering the incremental effort required for *Wireframe* modeling. Overall, the results of both methods are comparable in terms of total energy accuracy. Even when considering randomly generated sample sizes, both methods produced aggregate energy error between 6% and 12% which lie within acceptable parameters for large-scale energy reduction studies [54].

Individual BEM predictions can differ from measured data due to the uncertainty in occupancy patterns and it seemed therefore unlikely that the bottom-up methods would predict the energy use of Southern Ontario student residences with accuracy, particularly as the models were not based on building audits. However, the comparison of the aggregate annual measured consumption to simulated consumption resulted in percentage error ranges between 4% and 17% for total energy loads, and 6% to 31% for total heating loads in all four building categories. These error ranges are similar to the total aggregate energy range of 1% and 19% reported in [64, 65, 66], and the total heating energy range of 7% and 21% reported in [27, 67, 68, 69]. As one would expect, it is easier to predict aggregate energy than individual building energy with the use of reference models, which is why the total energy RMSE of all four building categories ranges from 10% to 26%. This RMSE range is also comparable to building level results from a regional stock study which reported an error range of 12% to 55% [70] and urban model studies which reported error ranges between 5% to 99% [71, 68, 72]. The ability of bottom-up methods to support energy and carbon reduction studies certainly depends on how reliable the simulation results are. Bottom-up methods for large-scale analysis are not as effective at predicting individual building consumption due to occupancy and operational patterns. However, individual building energy results from *Wireframe* and *Reference* method predictions of this thesis only differed by a RMSE of 5% in Lowrise models while both Midrise and Highrise models presented no statistically significant difference between the methods. Although bottom-up engineering methods using reference models to predict consumption are not commonly used for individual building

consumption studies, this study proves that the accuracy of the *Reference* method is almost as good as the *Wireframe* method for individual building analysis.

Previous large-scale bottom-up consumption prediction studies have found that simulation error tends to decrease with higher construction standards [55]. Although predicted heating results of this thesis support previous findings (Figure 65), where post-1980 student residence categories had lower aggregate heating errors than those obtained with pre-1980 categories, it was also found that post-1980 categories had the largest variation between *Reference* and *Wireframe* predictions, contrary to the hypothesis, even though post-1980 categories had higher thermal resistivity values. This was unexpected, as one would assume that a model with high thermal resistivity values would be less influenced by the form and orientation of a building, since higher performance envelopes manage heat more effectively.



**Figure 65.** Heating Percentage Error produced by each category using Wireframe and Reference methods

After inspecting heating variation between *Wireframe* and *Reference* methods, it was determined that post-1980 Lowrise buildings had significant area variation between each other, resulting the *Reference* model area to have a larger Area RMSE 19% when compared to that of other categories. This RMSE represents how similar the *Reference* model area is to individual measured building areas. A *Reference* model area with high RMSE suggests that the category, which the model represents, should be further subdivided by building area. It is a possible that if this is not addressed the heating percentage error between the methods will likely differ, which is the case in post-1980 Lowrise predictions, as the *Reference* model area does not accurately represent all buildings of the category.

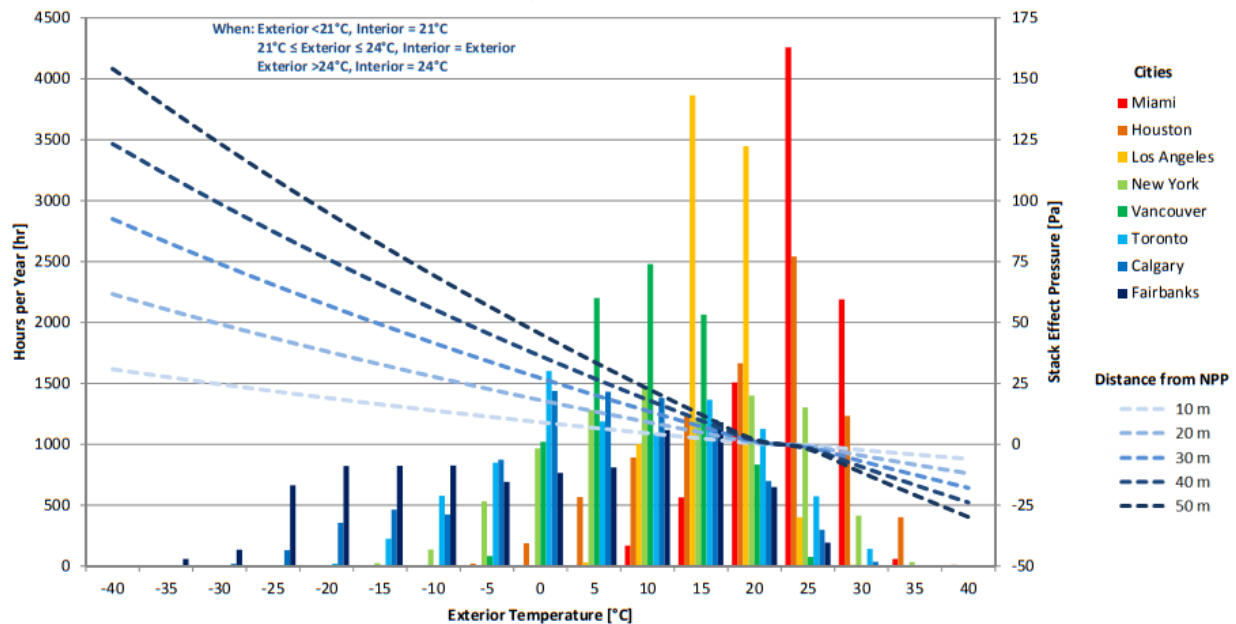
The other category with significant variation between *Wireframe* and *Reference* model heating predictions is the post-1980 Midrise. This category does not have an extremely high Area RMSE (12% for *Reference* model), however it does have a *Wireframe* model (*The Pond*) that was identified as a potential limitation of the *Wireframe* approach. *The Pond* residence has the highest heating use of the post-1980 Midrise category. This residence was modeled as two buildings as seen in (Figure 66). This is a modeling error; however, this is an issue that can be encountered by using the *Wireframe* method to predict consumption and should be discussed. In this scenario, *The Pond* residence was modelled with an increased surface area, which in turn increased heat loss.



**Figure 66.** The Pond residence was modelled as two independent buildings rather than one.

Another limitation of the *Wireframe* method is that it tends to use larger or smaller areas than what is measured. Using different areas to those measured can produce an over-prediction or an under-prediction in consumption. For example, post-1980 Lowrise *Wireframe* models considered a 4% larger area than what was measured, which for this category caused the *Wireframe* model predictions to decrease their Percentage Error by increasing the category's total energy consumption. Originally, it was thought that the *Wireframe* method would be able to predict heating consumption with more accuracy for buildings with complex geometry, however, after encountering limitations of the *Wireframe* method, this does not appear to be true. To ensure the performance of *Wireframe* models, the modeler must ensure models accurately represent the building, which might be challenging when aiming to predict the consumption of dozens or hundreds of buildings.

An interesting find of this thesis is that the *Reference* method predicted consumption with similar accuracy to that produced with the *Wireframe* method in Highrise buildings. This is likely due to the form of Highrise buildings, which tend to be relatively like each other. This suggests that for buildings with similar geometric complexity, the *Reference* method can predict consumption with similar or greater accuracy, as it considers measured areas to predict consumption, than by using an approach like the *Wireframe* method. As noted above, building categories that had high RMSE of *Reference* model area had the largest variation between *Wireframe* and *Reference* method predicted consumption, this was the case for all categories except the pre-1980 Highrise category. The reason why the pre-1980 Highrise category was not as affected by having high area deviations in its sample is due to the form of most buildings part of this category. Highrise buildings are tall structures that commonly follow a simple geometry. The large Area RMSE of the Highrise category is due to some of its buildings having a few more stories than the rest. Perhaps the Percentage Errors would have been greater if Highrise buildings considered in this study had significant height deviations, as a 50-floor building will most likely have different consumption levels when compared to a 20-floor building due to pressure differentials produced by the environment at different heights (Figure 67).



**Figure 67.** Stack effect pressure variability in buildings of different heights [73]

## 8.1 Error Discussion

This section displays limitations of this study, particularly those related to model predictions. Reference models created for this study are quite simple. Developing simple energy models was decided early on, as many energy models needed to be simulated, in addition to the ability of creating characterization templates that could be easily applied to thermal zoning schemes. Energy models presented in this thesis were subdivided into five thermal zones, four perimeter zones and one core. Even though the models were divided into different thermal zones, all considered the same activity template. Therefore, the models could be considered as single zone energy models, that are known to have limitations in predicting accurate cooling loads [55]. Additionally, conditioning setpoints of the energy models were defined at 21°C for both cooling and heating. This setpoint is atypical in Canada, where it is more common to use 22°C heating and 24-26°C cooling setpoints. The difference in common conditioning setpoints and values used in the energy models can lead to an under-estimation of heating and an over-estimation of cooling loads, however this 21°C setpoint was taken from DOE model inputs and were therefore assumed suitable for this study. Another limitation of the simulation predictions is the Weather file selected for simulations. Models were compared against measured 2013 data and therefore a 2013 Weather file should have been selected to run simulations. The CWEC Toronto Weather file contains hourly weather observations to represent an artificial one-year period specifically designed for energy calculations. This weather file is required by the NECB to be used for energy performance path studies, however, a measured 2013 Toronto EPW weather file could have produced more accurate results. Other limitations of this study regard to their characterization inputs. For starters, not all buildings have their construction period disclosed, which results in vintage assumptions. Additionally, the vintages used to define templates are based on initial construction dates and do not consider if a building has been renovated or retrofitted. This assumption may cause the energy models to have lower performance than what is in place. Moreover, U.S. DOE reference models that use actual survey data were not available for the Highrise Apartment model and therefore the 2004 DOE prototypical model of Highrise Apartments had to be considered. Lastly, post-1980 buildings have larger variability than pre-1980 categories, this can alter results as pre-1980 buildings will all be relatively similar while post-1980 buildings can go from very efficient (2004 vintage) to very inefficient (1981 vintage).

## 8.2 Future Research

This thesis evaluated two methods for estimating institutional building energy use to inform resource and emission reduction strategies. The purpose of this work was to identify an approach that would be suitable to inform better policy and incentives for Ontario's institutional sector. The methods that were explored are based on bottom-up engineering models that rely on reference energy models. Defined reference models were based on U.S. DOE commercial reference buildings due to data scarcity, however, this work could be improved by considering real data from the institutional sector. Institutional reference models will be necessary in years to come to better define policy and incentives, therefore, developing reference models that accurately represent the institutional building stock is of critical importance. A limitation of this study is that only one window-to-wall ratio was considered for all buildings. This was done to be able to compare the methods across categories, however, considering different glazing ratios could change the results presented in this thesis and should be further explored. Thermal zoning was also a stationary value for all buildings. Considering more complex zoning layouts and assigning different activity templates to the zones would also build upon this research. One of the benefits of the *Wireframe* method is that it allows for multiple buildings to be simulated at once. Comparing *Wireframe* predictions that considered all buildings part of an institution against *Reference* predictions would also allow to better understand the merits of each method, as all buildings from an institution would be simulated at once, where microclimate phenomena and the effect of adjacent buildings would be considered in *Wireframe* method predictions but not in *Reference* method predictions.

## 8.3 Research Implications

To manage and reduce emissions caused from the built environment, cities and provinces need to better understand both which buildings generate those emissions and the potential effects of energy retrofit programs and energy infrastructure changes. This thesis demonstrates that there is significant value in the *Reference* method for large-scale simulation and that the results obtained with the approach are like those obtained through a more detailed geometric analysis. This research is now serving as the basis for a district-scale simulation project at Ryerson University.

In addition, this thesis lays the foundation for future institutional reference model development while also identifies post-secondary building operations which can be used to represent both colleges and universities.

## 9 Conclusions

Through the analysis of these results, it was determined that there is no drastic difference between *Wireframe* and *Reference* methods. The *Wireframe* models need to be carefully revised to ensure no modeling geometric errors are encountered, while the classification or segmentation process of a building stock is of critical importance to predict consumption accurately with the *Reference* method.

The key findings of this research can be summarized as follow:

1. Area classifications are significantly important for the *Reference* method.
2. *Wireframe* models are prone to more simulation errors due to complex geometries.
3. For institutional carbon reduction studies, the *Reference* method can predict similar total energy results to those produced with the *Wireframe* method.
4. Random sampling study suggests that the methods differ by less than 2% for a range of sample sizes (up to 20).
5. *Wireframe* will tend to predict larger consumption as these models have larger surface-to-volume ratios when compared to *Reference* method models.
6. Student residences vary the least between college and university buildings.
7. Categories with high RMSE of *Reference* simulated area can produce prediction errors.
8. *Wireframe* and *Reference* method electricity predictions do not differ significantly.
9. *Wireframe* and *Reference* method predictions for total heating do differ, however, the difference between the methods is not substantial considering the difference in effort.
10. The *Reference* method can produce as good or better results than the *Wireframe* method for buildings with non-complex geometries.

For planners and policy makers, the *Reference* method could be used to analyze the existing institutional stock to inform retrofit policies and incentives. The only added benefit of considering the *Wireframe* method, which was not explored in this thesis, is the effect that adjacent buildings and micro-climate phenomena can have on buildings. For large scale energy efficiency studies, where measured data is available, which is the case for Ontario institutional buildings, the *Reference* method is recommended as it requires less simulation time, will always use the real area of a building to predict its consumption, and allows reference models to be created with more complex thermal zoning schemes.



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## **Appendix A:** Post-Secondary Energy Benchmarks by Building Type



## Student Residence Buildings - Colleges

Table A.1 - Initial sample of college residence buildings considered for benchmarking study.

Student Residences - Colleges						
College	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca	Newnham	1	8682045	35982	241	22
Centennial	Scarborough	1	6321924	15122	418	39
St. Clair	Windsor	2	49002	279	176	16
Humber	Lakeshore	1	3253092	15538	209	19
Humber	North	1	8865641	27087	327	30
Lambton	Sarnia	1	2556997	7757	330	31
Niagara	Welland	1	508040	6816	75	7
Sheridan	Oakville	1	5713929	16279	351	33

Table A.2 - Residence benchmarks without removing erroneous data entries.

Student Residences EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
188	256	241	330	142	-25	543	109	45%

Table A.3 - Residence benchmarks after removing erroneous data entries.

Residences EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
263	313	329	346	83	138	471	76	23%

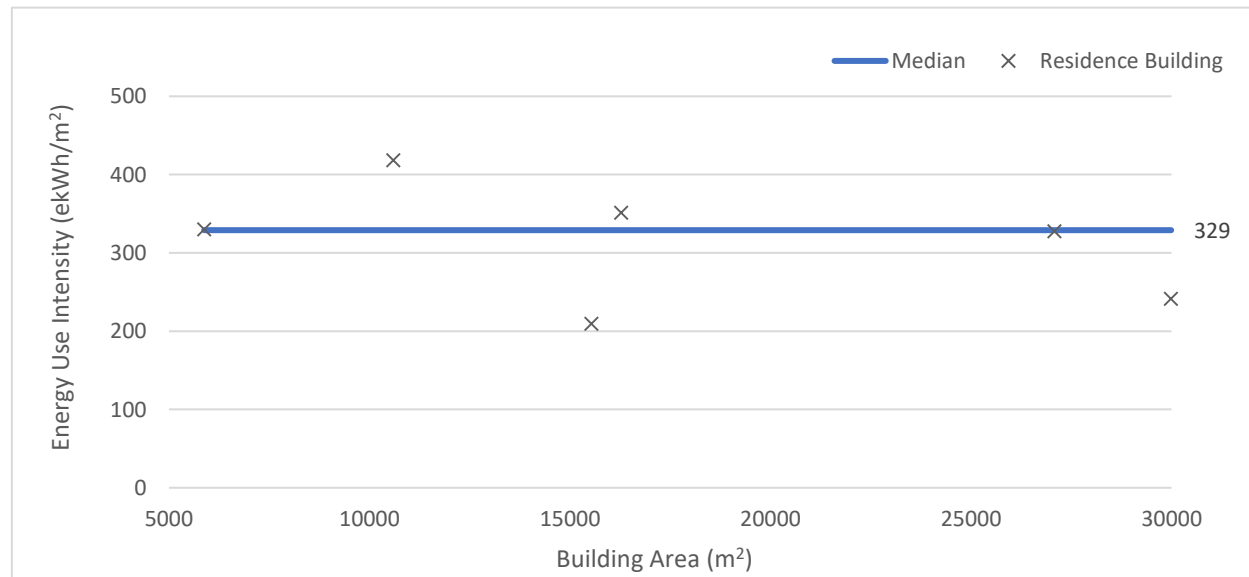


Figure A.1 - Residence buildings considered in the college developed benchmark

## Student Residence Buildings – University

Table A.4 - Initial sample of university residence buildings considered for benchmarking study.

Residences - Universities						
University	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
York	Toronto	16	53468115	138655	386	36
Brock	St. Catharines	3	6765013	38258	177	16

Table A.5 - Residence benchmarks without removing erroneous data entries.

Residences EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
302	364	388	450	148	80	672	107	27%

Table A.6 - Residence benchmarks after removing erroneous data entries

Residences EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
302	364	388	450	148	80	672	107	27%

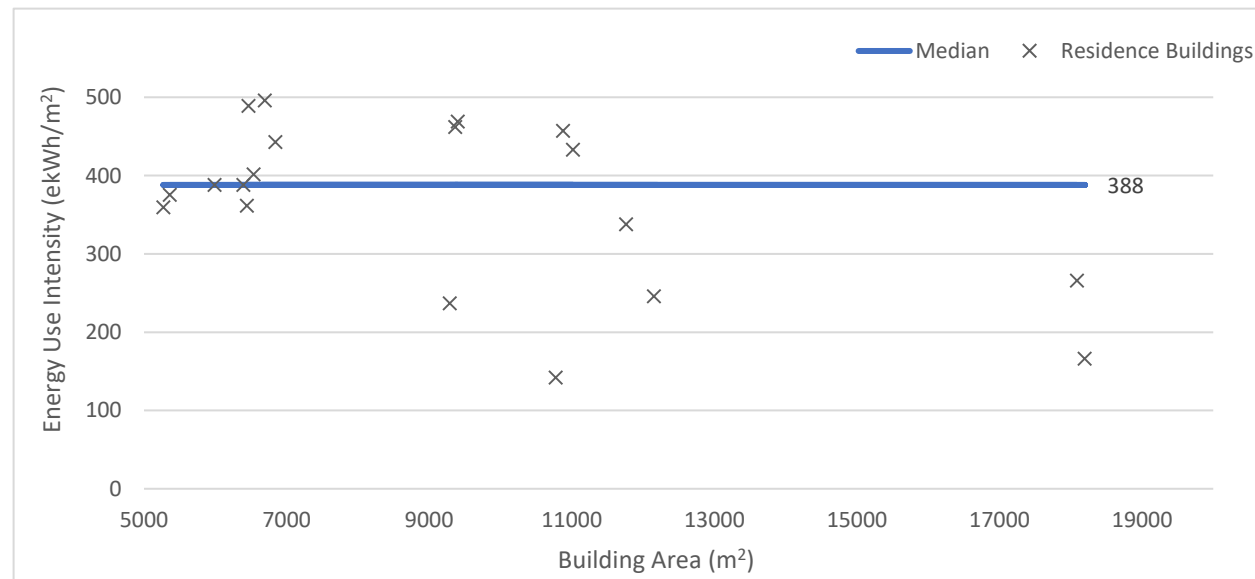


Figure A.2 - Residence buildings considered in the university developed benchmark.

## Student Residence Buildings – College and University

Table A.7 - Initial sample of university and college residence buildings considered for benchmarking study.

Residences – Colleges and Universities						
Operation	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca	Newnham	1	7236394	29990	241	22
Centennial	Scarborough	1	4432239	10602	418	39
St. Clair	Windsor	2	49002	279	176	16
St. Clair	Thames	1	1977532	5506	359	33
Humber	Lakeshore	1	3253092	15538	209	19
Humber	North	1	8865641	27087	327	30
Lambton	Sarnia	1	1938412	5880	330	31
Niagara	Welland	1	508040	6816	75	7
Sheridan	Oakville	1	5713929	16279	351	33
York	Toronto	16	53468115	138655	386	36
Brock	St. Catharines	3	6765013	38258	177	16

Table A.8 - Residence benchmarks without removing erroneous data entries.

Residences EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
241	331	359	418	177	-24	683	115	32%

Table A.9 - Residence benchmarks after removing erroneous data entries

Residences EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
281	352	361	430	148	59	652	99	27%

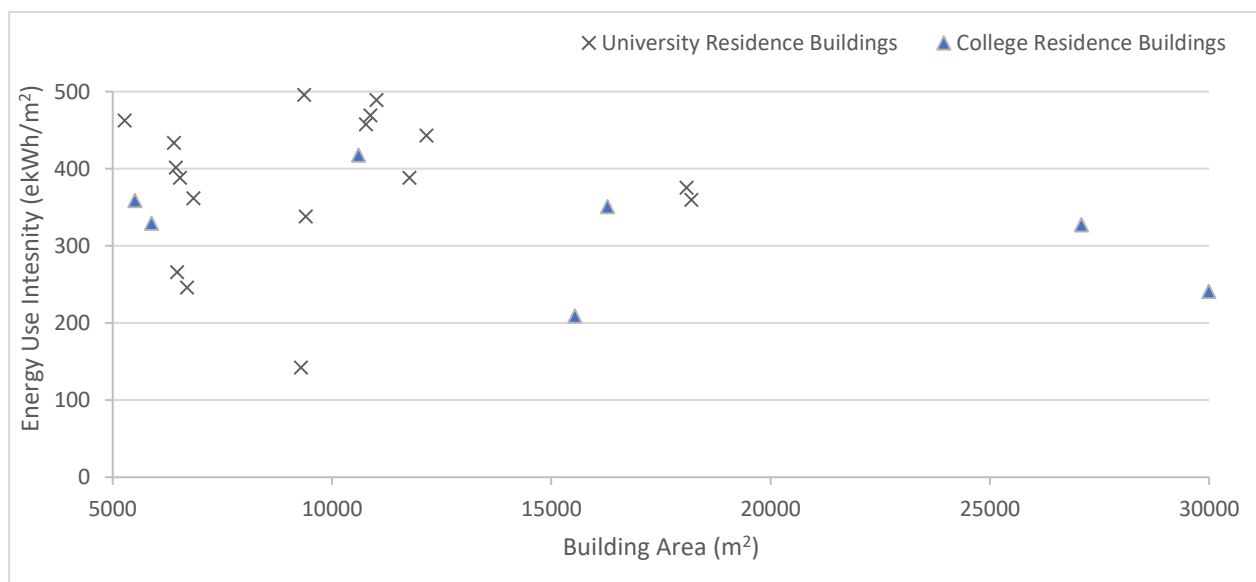


Figure A.3 - Residence buildings considered in the university and college developed benchmark.

## Laboratory Buildings – College

Table A.10 - Initial sample of college Laboratory buildings considered for benchmarking study.

Laboratories - Colleges						
College	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca	Newnham	5	2605207	8914	292	27
Centennial	Scarborough	6	13459595	32814	410	38
St. Clair	Windsor	4	3302449	14649	225	21
St. Clair	Thames	1	199677	717	278	26
Seneca	Jane	1	475791	1041	457	42
Seneca	York	2	1472463	8047	183	17
Lambton	Sarnia	7	3580987	8645	414	38
Niagara	Welland	1	1010532	6823	148	14

Table A.11 - Laboratory benchmarks without removing erroneous data entries.

Laboratories EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
211	343	278	410	198	-86	707	208	75%

Table A.12 – Laboratory benchmarks after removing erroneous data entries

Laboratories EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
210	281	240	336	126	22	525	98	41%

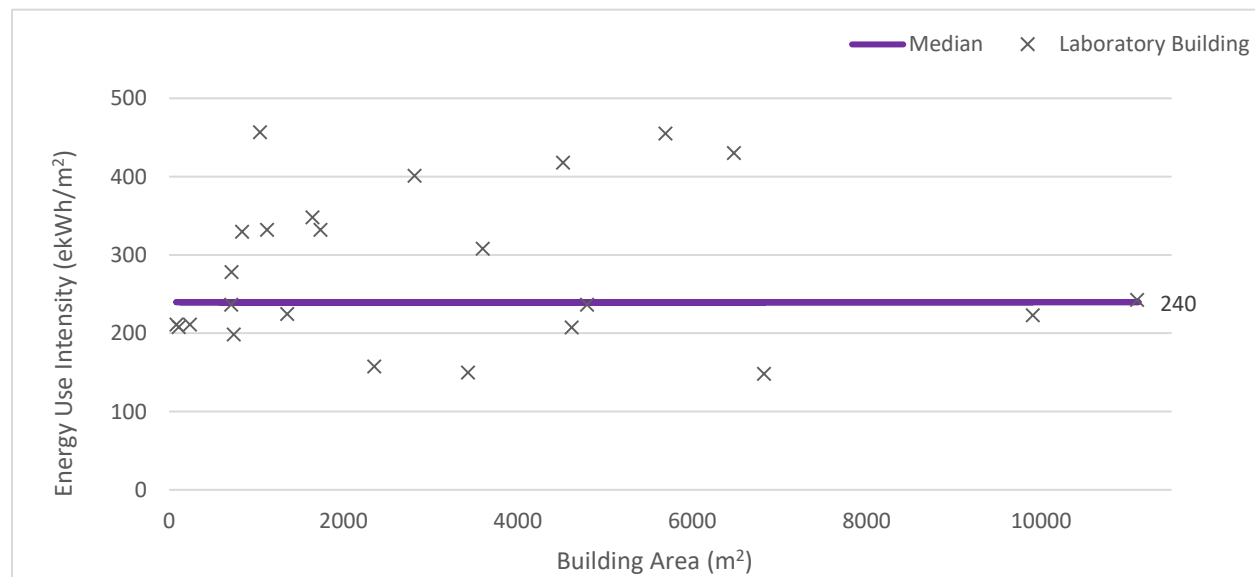


Figure A.4 – Laboratory buildings considered in the college developed benchmark.

## Laboratory Buildings – University

Table A.13 - Initial sample of university Laboratory buildings considered for benchmarking study.

Laboratories - Universities						
University	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
York	Toronto	6	61475596	93188	660	61
Brock	St Catharines	1	17218666	16367	1052	98
Ontario	Oshawa	1	6971337	11827	589	55

Table A.14 - Laboratory benchmarks without removing erroneous data entries.

Laboratories EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
502	619	623	644	141	290	856	190	31%

Table A.15 – Laboratory benchmarks after removing erroneous data entries

Laboratories EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
501	565	606	644	143	287	858	106	17%

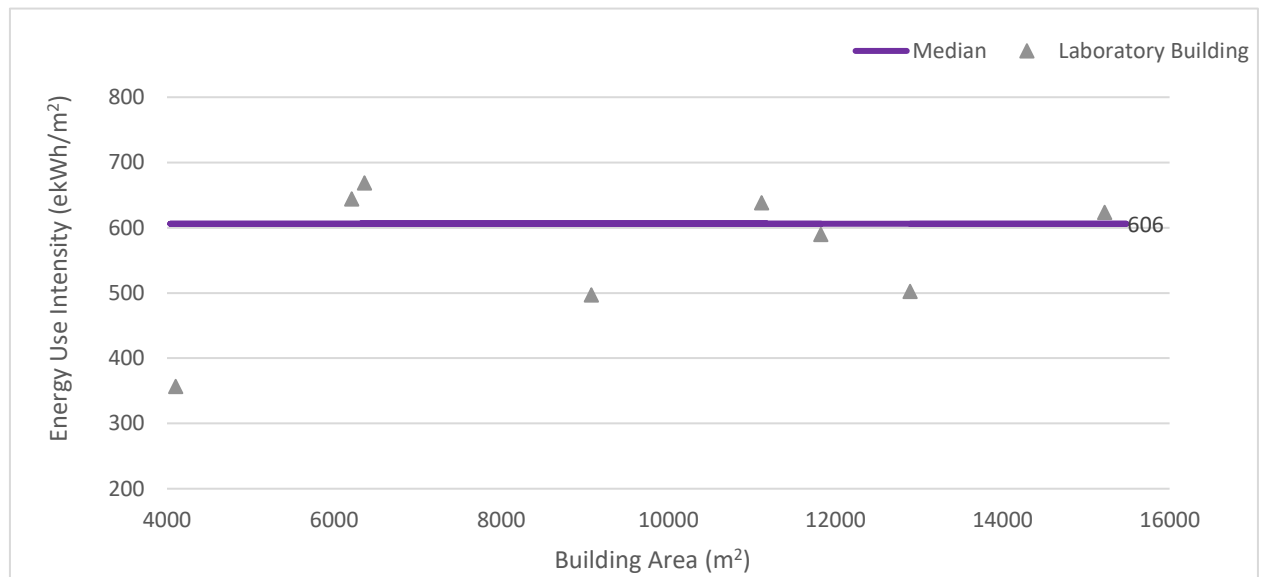


Figure A.5 - Laboratory buildings considered in the university developed benchmark.

## Laboratory Buildings – College and University

Table A.16 - Initial sample of college and university Laboratory buildings considered for benchmarking study.

Laboratories – Colleges & Universities						
Operation	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Seneca	Newnham	5	2605207	8914	292	27
Centennial	Scarborough	6	13459595	32814	410	38
St. Clair	Windsor	4	3302449	14649	225	21
St. Clair	Thames	1	199677	717	278	26
Seneca	Jane	1	475791	1041	457	42
Seneca	York	2	1472463	8047	183	17
Lambton	Sarnia	7	3580987	8645	414	38
Niagara	Welland	1	1010532	6823	148	14
York	Toronto	6	61475596	93188	660	61
Brock	St Catharines	1	17218666	16367	1052	98
Ontario	Oshawa	1	6971337	11827	589	55

Table A.17 - Laboratory benchmarks without removing erroneous data entries.

Laboratories EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
223	373	332	457	234	-128	808	198	60%

Table A.18 - Laboratory benchmarks after removing erroneous data entries.

Laboratories EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
220	347	331	456	235	-133	808	159	48%

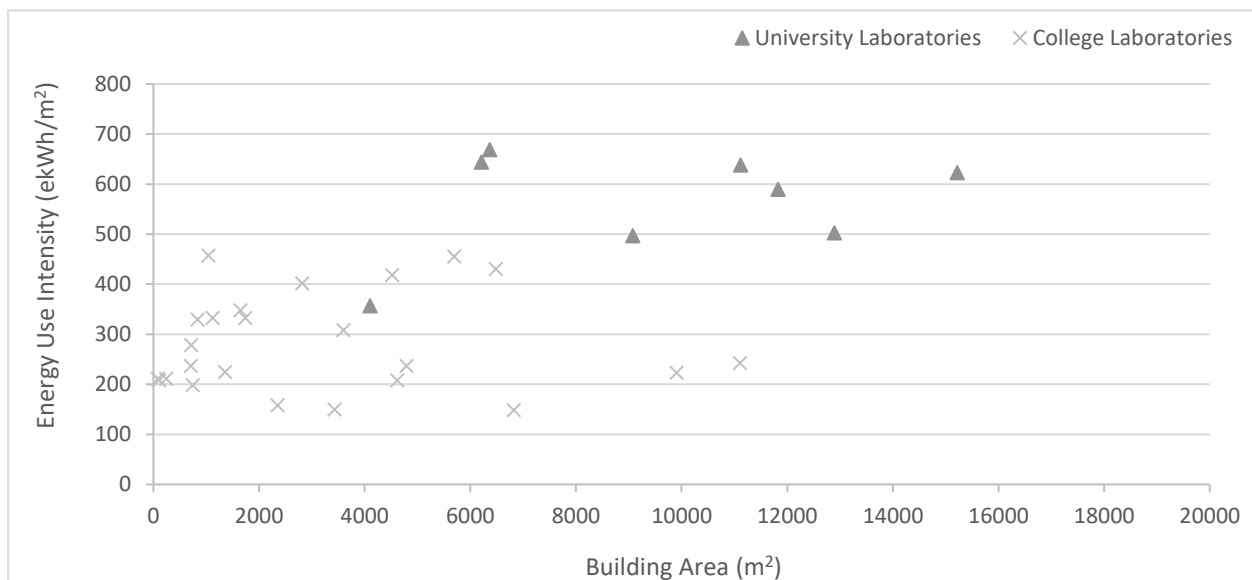


Figure A.6 - Laboratory buildings considered in the college and university developed benchmark.

## Classroom and Related Facilities – College

Table A.19 - Initial sample of college Classroom and Related Facilities considered for benchmarking study.

Classrooms and Related Facilities - Colleges						
College	Campus	n	Σ (kWh)	ΣArea (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Lambton	Sarnia	5	7056923	16516	427	40
St. Clair	Thames	1	2273758	6956	327	30
St. Clair	Windsor	2	53221552	109382	487	45
Seneca	Newnham	10	8512740	32965	258	24
Seneca	Jane	1	210831	461	457	42
Seneca	York	2	2775512	14706	189	17
George Brown	Casa Loma	4	17131034	59020	290	27
George Brown	St. James	5	25953198	63086	411	38
George Brown	Waterfront	1	5461829	34329	159	15
Centennial	Scarborough	9	10653618	34099	312	29
Humber	North	1	41020260	120329	341	32
Humber	Lakeshore	6	18449929	63404	291	27
Sheridan	Trafalgar	9	42694827	61384	696	64

Table A.20 – Classrooms and Related Facility benchmarks without removing erroneous data entries.

Classrooms and Related Facilities EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
234	394	328	447	213	-86	766	292	89%

Table A.21 – Classrooms and Related Facility benchmarks after removing erroneous data entries.

Classrooms and Related Facilities EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
218	323	308	406	187	-63	687	135	44%

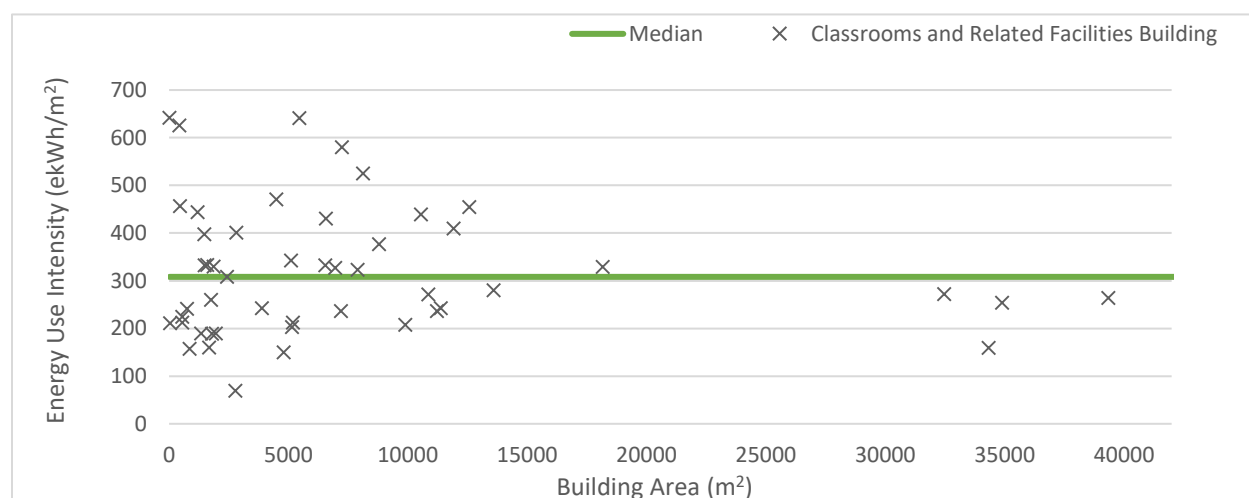


Figure A.7 - Classroom buildings considered in the college developed benchmark.

## Classroom and Related Facilities – University

Table A.22 - Initial sample of university Classroom and Related Facilities considered for benchmarking study.

Classrooms and Related Facilities - University					
Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Ontario Institute of Technology	4	24160839	53594	451	42
Trent University	1	1507708	4571	330	31
McMaster University	1	1703829	8361	204	19
McMaster University	1	215859877	431480	500	46
York University	12	50195435	158555	317	29
Brock University	1	3849143	6729	572	53
Brock University	12	140063790	178707	784	73
University of Toronto - St George	1	731480199	1367051	535	50
University of Toronto Scarborough	1	71162965	129817	548	51
University of Toronto Mississauga	1	93473003	185484	504	47
Ryerson University	1	103099956	328515	314	29

Table A.23 – Classrooms and Related Facility benchmarks without removing erroneous data entries.

Classrooms and Related Facilities EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
280	393	336	482	19	-2	73	16	50%

Table A.24 – Classrooms and Related Facility benchmarks after removing erroneous data entries.

Classrooms and Related Facilities EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
278	378	335	475	18	-2	72	14	44%

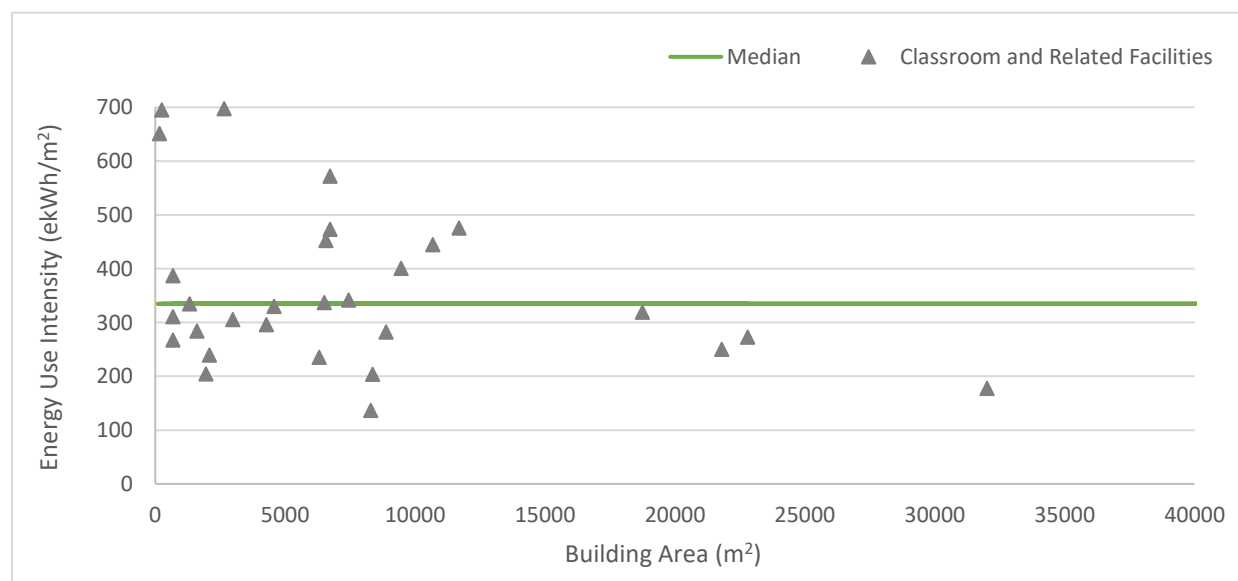


Figure A.8 - Classroom buildings considered in the university developed benchmark.



## Student Recreational Facilities – College

Table A.25 - Initial sample of college Student Recreational buildings considered for benchmarking study.

Student Recreational Facilities - Colleges						
College	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Lambton	Sarnia	1	512631	1127	455	42
St. Clair	Thames	1	1977532	5506	359	33
Centennial	Scarborough	5	6521464	21382	305	28
Seneca	Newnham	1	1843592	5535	333	31
Seneca	York	1	309932	1493	208	19
Sheridan	Trafalgar	2	2771206	4513	614	57
Niagara	Welland	1	200376	807	248	23

Table A.26 – Student Recreational building benchmarks without removing erroneous data entries.

Student Recreational Facilities EUI (ekWh/m <sup>2</sup> ) Before Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
293	382	376	436	143	78	651	139	37%

Table A.27 – Student Recreational building benchmarks after removing erroneous data entries.

Student Recreational Facilities EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
293	358	359	412	119	115	590	114	32%

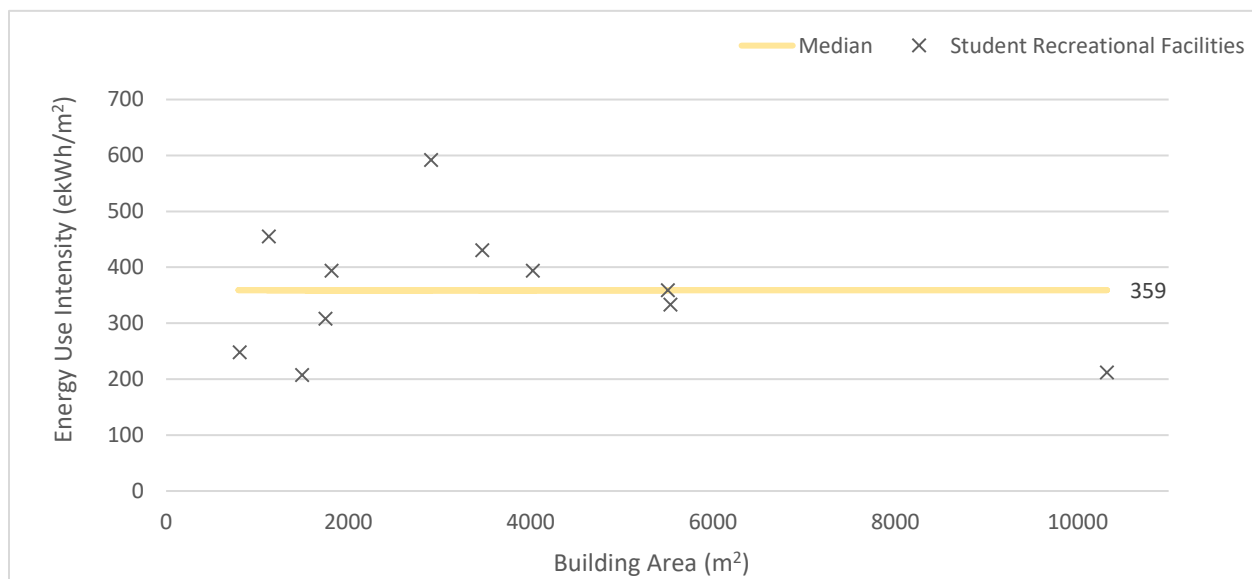


Figure A.9 – Student Recreational buildings considered in the college developed benchmark.

## Student Recreational Facilities – University

Table A.28 - Initial sample of university Student Recreational buildings considered for benchmarking study.

Student Recreational Facilities - University						
University	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Of Ontario	Oshawa	2	5730822	11654	492	46
York	Toronto	3	7318887	18690	392	36

Table A.29 – Student Recreational building benchmarks after removing erroneous data entries.

Student Recreational Facilities EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
299	402	340	561	262	-94	954	203	60%

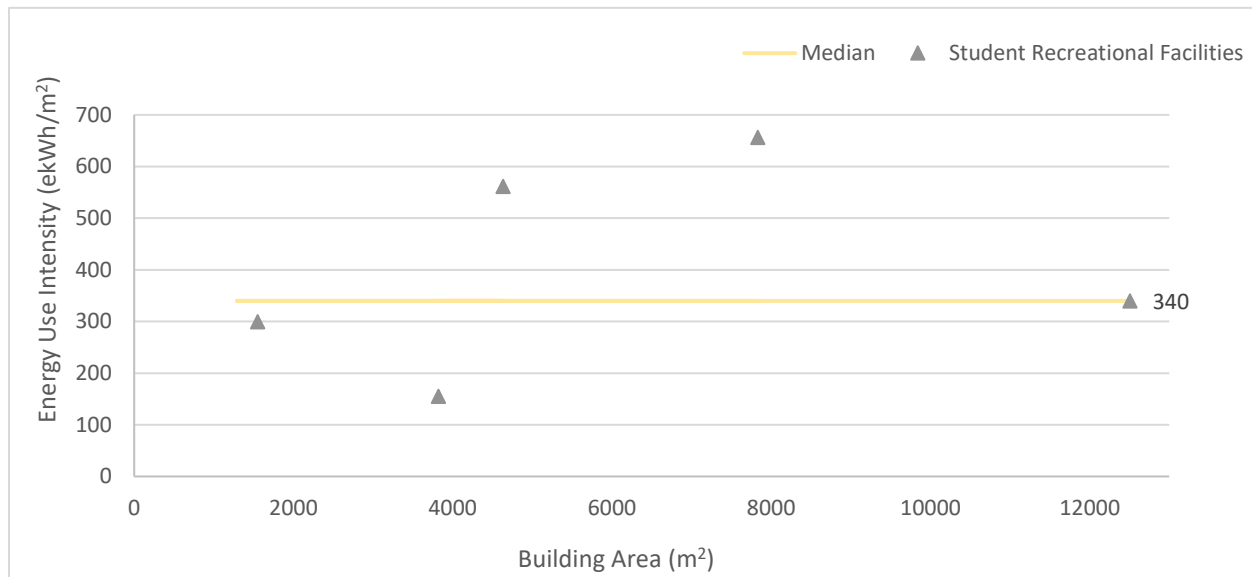


Figure A.10 – Student Recreational buildings considered in the university developed benchmark

## Student Recreational Facilities – College and University

Table A.30 - Initial sample of college and university Student Recreational buildings considered for benchmarking

Student Recreational Facilities – Colleges & Universities						
Operation	Campus	n	$\Sigma$ (kWh)	$\Sigma$ Area (m <sup>2</sup> )	ekWh/m <sup>2</sup>	ekWh/ft <sup>2</sup>
Lambton	Sarnia	1	512631	1127	455	42
St. Clair	Thames	1	1977532	5506	359	33
Centennial	Scarborough	5	6521464	21382	305	28
Seneca	Newnham	1	1843592	5535	333	31
Seneca	York	1	309932	1493	208	19
Sheridan	Trafalgar	2	2771206	4513	614	57
Niagara	Welland	1	200376	807	248	23
Ontario	Oshawa	2	5730822	11654	492	46
York	Toronto	3	7318887	18690	392	36

Table A.31 – Student Recreational building benchmarks after removing erroneous data entries.

Student Recreational Facilities EUI (ekWh/m <sup>2</sup> ) After Outlier Removal								
Q1	Mean	Median	Q3	IQR	LAV	UAV	s	s (%)
299	388	359	455	156	66	688	154	43%

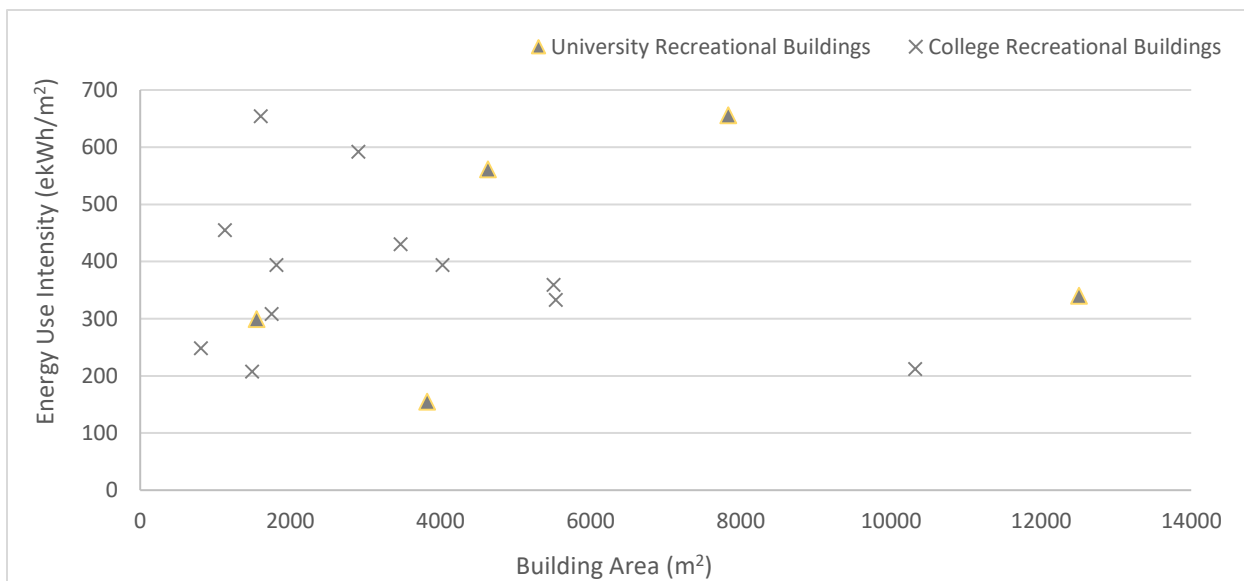


Figure A.11 – Student Recreational buildings considered in the college and university developed benchmark

## **Appendix B:** Reference Building Model Comparison and Sources

## Pre-1980 Lowrise: Form Comparison

Building form variables	Small Hotel	Mid-rise Apartment	Low-rise
Vintage	Pre 1980	Pre 1980	Pre 1980
Total conditioned area	4014m <sup>2</sup>	3135m <sup>2</sup>	6053m <sup>2</sup>
Number of floors	4	4	4
Building height	11.6m	12.2m	12.7m
Aspect Ratio	3	2.7	n/a
Window to wall ratio	11%	15%	n/a
Shading	None	None	None
Ground floor to ceiling height	3.35m	3.05m	n/a
Floor to floor height	2.74m	3.05m	n/a
Building shape	Rectangle	Rectangle	Rectangle
Source	[1]	[2]	[3]

## Pre-1980 Lowrise: Form Selection

Pre-1980 Lowrise_student residence		
Characterization inputs	Reference Method	Wireframe Method
Total conditioned area	6053 m <sup>2</sup>	GIS/DaftLogic defined
Number of floors	4	DaftLogic defined
Building height	12m	GIS/DaftLogic defined
Aspect Ratio*	3	GIS/DaftLogic defined
Window to wall ratio*	30%	30%
Shading	None	None
Floor to floor height*	3m	3m
Building shape	Rectangle	GIS defined

\* Aspect ratio of the DOE Small Hotel is considered to represent pre-1980 Lowrise models

\* Window-to-wall ratio of 30% was defined as this ratio was common in student residence buildings

\*Floor-to-floor height was set as 3m in all categories.

## Pre-1980 Lowrise: Fabric Comparison

Pre-1980 Small Hotel		Pre-1980 Midrise Apartment	
		Ground floor slab	
Name	ext-slab-mass	ext-slab-mass	
Layer 1	HW CONCRETE	HW CONCRETE	
Layer 2	CP02 CARPET PAD	CP02 CARPET PAD	
R-value	0.54 m²*K/W	0.54 m²*K/W	
		Ceiling	
Name	Typical interior ceiling	Floor Adiabatic construction	
Layer 1	CP02 CARPET PAD	CP02 CARPET PAD	
Layer 2	100mm Normalweight concrete floor	100mm Normalweight concrete floor	
Layer 3	-	Nonres_Floor_Insulation	
		Exterior roof	
Name	Typical Wood Joist Attic Floor R-16.67	Typical IEAD Roof R-16.67	
Layer 1	5/8 in. Gypsum Board	Roof Membrane	
Layer 2	Typical Insulation R-15.03	Typical Insulation R-15.55	
Layer 3	-	Metal Roof Surface	
R-value	2.99 m²*K/W	2.99 m²*K/W	
		Exterior wall	
Name	Insulated Steel Framed Exterior Wall R-6.9	Insulated Steel Framed Exterior Wall R-6.9	
Layer 1	25mm Stucco	25mm Stucco	
Layer 2	5/8 in. Gypsum Board	5/8 in. Gypsum Board	
Layer 3	Typical Insulation R-4.72	Typical Insulation R-4.72	
Layer 4	5/8 in. Gypsum Board	5/8 in. Gypsum Board	
R-value	1.22 m²*K/W	1.22 m²*K/W	
		Interior wall	
Name	Typical Interior Wall	Typical Interior Wall	
Layer 1	G01 13mm gypsum board	G01 13mm gypsum board	
Layer 2	G01 13mm gypsum board	G01 13mm gypsum board	
		Interior floor	
Name	Typical Interior Floor	Floor Adiabatic construction	
Layer 1	100mm Normalweight concrete floor	CP02 CARPET PAD	
Layer 2	CP02 CARPET PAD	100mm Normalweight concrete floor	
Layer 3	-	Nonres_Floor_Insulation	
		Glazing System	
Name	U 0.62 SHGC 0.41 Simple Glazing Window	U 0.62 SHGC 0.41 Simple Glazing Window	
Layer 1	U 0.62 SHGC 0.41 Simple Glazing	U 0.62 SHGC 0.41 Simple Glazing	
U-Factor	3.53 W/m²*K	3.53 W/m²*K	
		Internal mass	
Name	Interior Furnishings	Interior Furnishings	
Layer 1	Standard Wood 6inch	Standard Wood 6inch	
Source	[1]	[2]	

## Pre-1980 Lowrise: Fabric Selection

Pre-1980 Lowrise_student residence		
Component name	Assembly name	Assembly details
Ground floor slab	ext-slab-mass	1.22 m <sup>2</sup> *K/W
Exterior roof	Typical IEAD Roof R-16.67	2.99 m <sup>2</sup> *K/W
Exterior wall	Insulated Steel Framed Exterior Wall R-6.9	1.22 m <sup>2</sup> *K/W
Ceiling	Typical Interior Ceiling	-
Interior walls	Typical Interior Wall	-
Interior floor	Typical Interior Floor	-
Internal mass	Interior Furnishings	-
	U-Factor	3.53 W/ m <sup>2</sup> *K
Glazing system	SHGC	0.41
	Visible transmittance	0.32
Air tightness	ACH@75Pa	0.92

## Pre-1980 Lowrise: Space Activity Comparison

Pitman Hall		Small Hotel		Midrise Apartment	
Space Activity	Area	Space Activity	Area	Space Activity	Area
Administrative offices	1%	Basement	17%	Apartment	87%
Common use	6%	Retail	1%	Corridor	10%
Food services	3%	Mechanical	1%	Office	3%
Residence living	43%	Storage	1%		
Residence service	4%	Laundry	1%		
Washrooms	2%	Cafe	2%		
Corridors	20%	Lobby	12%		
Non- assignable space	10%	Corridor	17%		
Parking structure	11%	Dining	3%		
Source	[4]		[1]		[2]

## Pre-1980 Lowrise: Space Activity Selection

Pre-1980 Lowrise_Student Residence	
Space Activity	Area
Student room	87%
Corridor	10%
Office	3%

## Pre-1980 Lowrise: Occupancy Comparison

Pre-1980 Small Hotel				Pre-1980 Mid-rise			
Space activity	Occupancy per space	Occupancy density	Source	Space activity	Occupancy per space	Occupancy density	Source
Guest room	1.5 pax	26 m <sup>2</sup> /pax	[5]	Apartment	2.5 pax	35 m <sup>2</sup> /pax	[5]
Office	2 pax	44 m <sup>2</sup> /pax	[5]	Office	2 pax	44 m <sup>2</sup> /pax	[5]

## Pre-1980 Lowrise: Occupancy Selection

Pre-1980 Lowrise_Student Residence			
Space activity	Building area	Occupancy density from DOE models	Weighted Occupancy density
Student room	87%	26 m <sup>2</sup> /pax	30.7
Office	3%	44 m <sup>2</sup> /pax	1.3
Corridor	10%	0	0
Weighted Average Pre-1980 Lowrise total peak occupancy density (m <sup>2</sup> /pax)			32

## Pre-1980 Lowrise: Ventilation Rate Comparison

Pre-1980 Small Hotel			Pre-1980 Midrise		
Space activity	Outdoor air	Source	Space activity	Outdoor air	Source
Hotel guest room	0.43 L/s/m <sup>2</sup>	[6]	Apartment	0.48 L/s/m <sup>2</sup>	[6]
Office	0.77 L/s/m <sup>2</sup>	[6]	Office	0.23 L/s/m <sup>2</sup>	[6]

## Pre-1980 Lowrise: Ventilation Rate Selection

Pre-1980 Lowrise_Student Residence			
Space activity	Building area	Outdoor air from DOE models	Weighted Outdoor air
Student room	87%	0.46 L/s/m <sup>2</sup>	0.42 L/s/m <sup>2</sup>
Office	3%	0.23 L/s/m <sup>2</sup>	0.01 L/s/m <sup>2</sup>
Corridor	10%	0.25 L/s/m <sup>2</sup>	0.03 L/s/m <sup>2</sup>
Weighted Average Pre1980 Low-rise total ventilation rate			0.45 L/s/m <sup>2</sup>



## Pre-1980 Lowrise: Lighting Power Density Comparison

Pre-1980 Small Hotel			Pre-1980 Midrise		
Space activity	Lights	Source	Space activity	Lights	Source
Hotel guest room	18.7 W/m <sup>2</sup>	[7]	Apartment	3.88 W/m <sup>2</sup>	[7]
Office	22 W/m <sup>2</sup>	[7]	Office	22 W/m <sup>2</sup>	[7]
Corridor	9.2 W/m <sup>2</sup>	[7]	Corridor	9.2 W/m <sup>2</sup>	[7]

## Pre-1980 Lowrise: Lighting Power Density Selection

Pre-1980 Lowrise Lighting Power Density			
Space activity	Building area	Lights from DOE models	Weighted Lights
Student room	87%	11.29 W/m <sup>2</sup>	9.82 W/m <sup>2</sup>
Office	3%	22 W/m <sup>2</sup>	0.66 W/m <sup>2</sup>
Corridor	10%	9.2 W/m <sup>2</sup>	0.92 W/m <sup>2</sup>
Weighted Average Pre1980 Low-rise total lighting loads			11.40 W/m <sup>2</sup>

## Pre-1980 Lowrise: Plug and Process Loads Comparison

Pre-1980 Small Hotel			Pre-1980 Midrise		
Space activity	Plug load	Source	Space activity	Plug load	Source
Hotel guest room	14.31 W/m <sup>2</sup>	[8]	Apartment	5.38 W/m <sup>2</sup>	[9]
Office	12.9 W/m <sup>2</sup>	[8]	Office	12.9 W/m <sup>2</sup>	[9]
Corridor	0	[8]	Corridor	0	[9]

## Pre-1980 Lowrise: Plug and Process Loads Selection

Pre-1980 Lowrise_Student Residence			
Space activity	Building area	Plug load from DOE models	Weighted Plug load
9.85 W/m <sup>2</sup>	8.57 W/m <sup>2</sup>	9.85 W/m <sup>2</sup>	8.57 W/m <sup>2</sup>
12.9 W/m <sup>2</sup>	0.39 W/m <sup>2</sup>	12.9 W/m <sup>2</sup>	0.39 W/m <sup>2</sup>
0	0	0	0
			8.95 W/m <sup>2</sup>
Weighted Average Pre1980 Low-rise total plug loads (including elevator)			9 W/m <sup>2</sup>

\* Plug loads must add 1900 kWh/year for elevators

\* 1900kWh/365 day \* hours of use \* (1000 W/ 1kWh)/ Reference Area (m<sup>2</sup>)

\* 1900kWh/365 day \* day/15.76 hours \* (1000 W/ 1kWh)/ (6035 m<sup>2</sup>) = 0.055 W/m<sup>2</sup>

## Pre-1980 Lowrise: Water System Comparison

Pre-1980 Small Hotel			Pre-1980 Midrise		
Space activity	DHW	Source	Space activity	DHW	Source
Hotel guest room	0.2 L/h/m <sup>2</sup>	[8]	Apartment	0.15 L/h/m <sup>2</sup>	[9]
Office	0		Office	0	
Corridor	0		Corridor	0	

## Pre-1980 Lowrise: Water System Selection

Pre-1980 Lowrise_Student Residence			
Space activity	Building area	DHW from DOE models	Weighted DHW
Student room	87%	0.20	0.175 L/h/m <sup>2</sup>
Office	3%	0	0
Corridor	10%	0	0
Weighted Average Pre1980 Low-rise total water system loads			0.175 L/h/m <sup>2</sup>

- \* Small Hotel water system loads are used to represent pre-1980 Lowrise student residence loads. The less efficient consumption was used for pre-1980 vintages.

## Pre-1980 Lowrise: Equipment Comparison

Pre-1980 Small Hotel		
Heating Type	Unit heater, PTAC electric heat	2003 CBECS
Cooling Type	DX	2003 CBECS
Fan Control	Constant	2003 CBECS
SWH Type	gas water heater	
Fuel	gas	
Cooling Efficiency	3.4	IDF Small Hotel input
Thermal Efficiency (%)	80	Winiarski and Halverson, 2008
Temperature Setpoint (°C)	60	

Pre-1980 Midrise		
Heating Type	Gas furnace	90.1 Mechanical Subcommittee
Cooling Type	Split system DX	90.1 Mechanical Subcommittee
Fan Control	CAV	90.1 Mechanical Subcommittee
SWH Type	Gas water heater	
Fuel	gas	
Cooling Efficiency	3.4	IDF Midrise Apartment input
Thermal Efficiency (%)	80	Winiarski and Halverson, 2008
Temperature Setpoint (°C)	60	

## Pre-1980 Lowrise: Equipment Selection

Pre-1980 Lowrise student residence	
Heating Type	Unit heater, PTAC electric heat
Cooling Type	Split system DX
Fan Control	CAV
SWH Type	gas water heater
Fuel	gas
Cooling Efficiency	3.4
Thermal Efficiency (%)	80
Temperature Setpoint (°C)	60

- \* The models will have a 21°C for both heating and cooling year around.
- \* Equipment COP will be set .8 for heating, and 3.4 for cooling (Pre1980 Small Hotel and Midrise).
- \* No economizer
- \* No natural ventilation is assigned

## Pre-1980 Lowrise: Schedule Selection

Occupancy Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	87%	1	1	1	1	1	1	1	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.3	0.52	0.87	0.87	1	1	1	1
	Office	3%	0	0	0	0	0	0	0	0	1	1	1	1	0.5	1	1	1	1	0	0	0	0	0	0	0
	BLDG_OCC_SCH	10%	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.5	0.7	0.7	0.8	0.9	0.9
DOE Midrise	Apartment_wknd	87%	1	1	1	1	1	1	1	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.3	0.52	0.87	0.87	1	1	1	1
	Office_WKND	3%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	BLDG_OCC_SCH_WKND	10%	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.6	0.6	0.6	0.7	0.7	0.7

Lighting Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	43%	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.6	0.8	1.0	1.0	0.7	0.4	0.2
DOE Small H	Guest Room	43%	0.2	0.2	0.1	0.1	0.1	0.2	0.4	0.6	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.7	0.9	1.0	0.9	0.7	0.3
DOE Midrise	Corridor	8%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DOE Midrise	Office_Ltg_Sch_Base	6%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DOE Midrise	Apartment	43%	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.6	0.8	1.0	1.0	0.7	0.4	0.2
DOE Small H	Guest Room_WKND	43%	0.3	0.3	0.1	0.1	0.1	0.1	0.4	0.4	0.6	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.9	1.0	1.0	1.0	0.9	0.4
DOE Midrise	Corridor	8%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DOE Midrise	Office_Ltg_Sch_Base	6%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Plug and Process Loads Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	92%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.7	0.69	0.66	0.65	0.68	0.8	1	1	0.93	0.89	0.85	0.71	0.58
DOE Midrise	Office	8%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.5	1	1	1	1	0.94	1	1	1	1	0.5	0.33	0.33	0.33	0.33	0.33	0.33
DOE Midrise	Apartment	92%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.7	0.69	0.66	0.65	0.68	0.8	1	1	0.93	0.89	0.85	0.71	0.58
DOE Midrise	Office	8%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Domestic Hot Water																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Small H	GuestRoom_STW_Sch	100%	0.2	0.15	0.15	0.15	0.2	0.35	0.6	0.8	0.55	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.55	0.4	0.4	0.6	0.45	0.25
DOE Small H	GuestRoom_STW_Sch wknd	100%	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.6	0.8	0.6	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.6	0.4

- \* Occupancy schedules: area weighted based on activity use percentages
- \* Lighting schedules: Area weighted average based on lighting density percentages. Space activities with highest LPD contribution to total lighting loads (W/m<sup>2</sup>) were used to define the whole building schedules.
- \* Plug and process schedules: Area weighted average based on plug and process load percentages.
- \* Domestic Hot Water: Area weighted average based on DHW percentages.

## Pre-1980 Lowrise: Sources

[1] 2003 CBECS Data

[2] PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York

[3] Mandatory Energy Reports 2013 – Ontario, Daft Logic, Visual Judgment, Geographical Information Systems, and the Architectural Conservancy of Ontario

[4] Ryerson Space Audit Data. URL: <https://ryerson.iwmsapp.com/archibus/>

[5] ASHRAE Standard 62.1-2004 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[6] ASHRAE Standard 62-1999 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[7] ASHRAE Standard 90.1-1989, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[8] PNNL - 17875 Technical Support Document: The Development of the Advanced Energy Design Guide for Highway Lodging Buildings

[9] DOE Commercial Reference Building Report

## Post-1980 Lowrise: Form Comparison

Building form variables	Small Hotel	Mid-rise Apartment	Low-rise
Vintage	Post 1980	Post1980	Post1980
Total conditioned area	4014m <sup>2</sup>	3135m <sup>2</sup>	9618m <sup>2</sup>
Number of floors	4	4	4
Building height	11.6m	12.2m	13.3m
Aspect Ratio	3	2.7	n/a
Window to wall ratio	11%	15%	n/a
Shading	None	None	None
Ground floor to ceiling height	3.35m	3.05m	n/a
Floor to floor height	2.74m	3.05m	n/a
Building shape	Rectangle	Rectangle	n/a
Source	[1]	[2]	[3]

## Post-1980 Lowrise: Form Selection

Post-1980 Lowrise_student residence		
Characterization inputs	Reference Method	Wireframe Method
Total conditioned area	9613 m <sup>2</sup>	GIS/DaftLogic defined
Number of floors	4	DaftLogic defined
Building height	12m	GIS/DaftLogic defined
Aspect Ratio*	3	GIS/DaftLogic defined
Window to wall ratio*	30%	30%
Shading	None	None
Floor to floor height*	3m	3m
Building shape	Rectangle	GIS defined

\* Aspect ratio of the DOE Small Hotel is considered to represent post-1980 Lowrise models

\* Window-to-wall ratio of 30% was defined as this ratio was common in student residence buildings

\*Floor-to-floor height was set as 3m in all categories.

## Post-1980 Lowrise: Fabric Comparison

Post 1980 Small Hotel		Post 1980 Mid-rise Apartment
<b>Ground floor slab</b>		
Name	ext-slab-mass	ext-slab-mass
Layer 1	HW CONCRETE	HW CONCRETE
Layer 2	CP02 CARPET PAD	CP02 CARPET PAD
R-value	0.54 m <sup>2</sup> *K/W	0.54 m <sup>2</sup> *K/W
<b>Ceiling</b>		
Name	INT-FLOOR-UNDERSIDE	INT-FLOOR-UNDERSIDE
Layer 1	CP02 CARPET PAD	CP02 CARPET PAD
Layer 2	MAT-CC05 4 HW CONCRETE	MAT-CC05 4 HW CONCRETE
<b>Exterior roof</b>		
Name	Attic Res Floor	IEAD Res Roof
Layer 1	1/2IN Gypsum	Roof Membrane
Layer 2	AtticFloor Res Insulation	IEAD RES Roof Insulation
Layer 3	1/2IN Gypsum	Metal Decking
R-value	3.97 m <sup>2</sup> *K/W	3.97 m <sup>2</sup> *K/W
<b>Exterior wall</b>		
Name	Steel Frame Res Ext Wall	Steel Frame Res Ext Wall
Layer 1	Wood Siding	Wood Siding
Layer 2	Steel Frame Res Wall	Steel Frame Res Wall
Layer 3	1/2IN Gypsum	1/2IN Gypsum
R-value	2.71 m <sup>2</sup> *K/W	2.71 m <sup>2</sup> *K/W
<b>Interior wall</b>		
Name	Int-walls	Int-walls
Layer 1	`	1/2IN Gypsum
Layer 2	1/2IN Gypsum	1/2IN Gypsum
<b>Interior floor</b>		
Name	INT-FLOOR-TOPSIDE	INT-FLOOR-TOPSIDE
Layer 1	MAT-CC05 4 HW CONCRETE	MAT-CC05 4 HW CONCRETE
Layer 2	CP02 CARPET PAD	CP02 CARPET PAD
<b>Glazing System</b>		
Name	Window Res Fixed	Window Res Operable
Layer 1	Res Fixed Assembly Window	Res Operable Assembly
U-Factor	2.95 W/m <sup>2</sup> *K	2.95 W/ m <sup>2</sup> *K
<b>Internal mass</b>		
Name	Interior Furnishings	Interior Furnishings
Layer 1	Standard Wood 6inch	Standard Wood 6inch
Source	[1]	[2]

## Post-1980 Lowrise: Fabric Selection

Post-1980 Lowrise_student residence		
Component name	Assembly name	Assembly details
Ground floor slab	ext-slab	0.54 m <sup>2</sup> *K/W
Exterior roof	IEAD Res Roof	3.97 m <sup>2</sup> *K/W
Exterior wall	Steel Frame Res Ext Wall	2.71 m <sup>2</sup> *K/W
Ceiling	INT-FLOOR-UNDERSIDE	-
Interior walls	Int-walls	-
Interior floor	INT-FLOOR-TOPSIDE	-
Internal mass	Interior Furnishings	-
Glazing system	U-Factor	2.95 W/ m <sup>2</sup> *K
	SHGC	0.39
	Visible transmittance	0.31
Air tightness	ACH@75Pa	0.92

## Post-1980 Lowrise: Space Activity Comparison

Pitman Hall		Small Hotel		Midrise Apartment	
Space Activity	Area	Space Activity	Area	Space Activity	Area
Administrative offices	1%	Basement	17%	Apartment	87%
Common use	6%	Retail	1%	Corridor	10%
Food services	3%	Mechanical	1%	Office	3%
Residence living	43%	Storage	1%		
Residence service	4%	Laundry	1%		
Washrooms	2%	Cafe	2%		
Corridors	20%	Lobby	12%		
Non- assignable space	10%	Corridor	17%		
Parking structure	11%	Dining	3%		
Source	[4]		[1]		[2]

## Post-1980 Lowrise: Space Activity Selection

Post-1980 Lowrise_Student Residence	
Space Activity	Area
Student room	87%
Corridor	10%
Office	3%



## Post-1980 Lowrise: Occupancy Comparison

Post-1980 Small Hotel				Post-1980 Mid-rise			
Space activity	Occupancy per space	Occupancy density	Source	Space activity	Occupancy per space	Occupancy density	Source
Guest room	1.5 pax	26 m <sup>2</sup> /pax	[5]	Apartment	2.5 pax	35 m <sup>2</sup> /pax	[5]
Office	2 pax	44 m <sup>2</sup> /pax	[5]	Office	2 pax	44 m <sup>2</sup> /pax	[5]

## Post-1980 Lowrise: Occupancy Selection

Post-1980 Lowrise_Student Residence			
Space activity	Building area	Occupancy from DOE models	Weighted Occupancy
Student room	87%	26 m <sup>2</sup> /pax	30.7
Office	3%	44 m <sup>2</sup> /pax	1.3
Corridor	10%	0	0
Weighted Average Post-1980 Lowrise total peak occupancy density (m <sup>2</sup> /pax)			32

## Post-1980 Lowrise: Ventilation Rate Comparison

Post-1980 Small Hotel			Post-1980 Midrise		
Space activity	Outdoor air	Source	Space activity	Outdoor air	Source
Hotel guest room	0.43 L/s/m <sup>2</sup>	[6]	Apartment	0.48 L/s/m <sup>2</sup>	[6]
Office	0.77 L/s/m <sup>2</sup>	[6]	Office	0.23 L/s/m <sup>2</sup>	[6]

## Post-1980 Lowrise: Ventilation Rate Selection

Post-1980 Lowrise_Student Residence			
Space activity	Building area	Outdoor air from DOE models	Weighted Outdoor air
Student room	87%	0.46 L/s/m <sup>2</sup>	0.42 L/s/m <sup>2</sup>
Office	3%	0.23 L/s/m <sup>2</sup>	0.01 L/s/m <sup>2</sup>
Corridor	10%	0.25 L/s/m <sup>2</sup>	0.03 L/s/m <sup>2</sup>
Weighted Average Post1980 Lowrise total ventilation rate			0.45 L/s/m <sup>2</sup>

## Post-1980 Lowrise: Lighting Power Density Comparison

Post-1980 Small Hotel			Post-1980 Midrise		
Space activity	Lights	Source	Space activity	Lights	Source
Hotel guest room	18.7 W/m <sup>2</sup>	[7]	Apartment	3.88 W/m <sup>2</sup>	[7]
Office	22 W/m <sup>2</sup>	[7]	Office	22 W/m <sup>2</sup>	[7]
Corridor	9.2 W/m <sup>2</sup>	[7]	Corridor	9.2 W/m <sup>2</sup>	[7]

## Post-1980 Lowrise: Lighting Power Density Selection

Post-1980 Lowrise Lighting Power Density			
Space activity	Building area	Lights from DOE models	Weighted Lights
Student room	87%	3.88 W/m <sup>2</sup>	3.38 W/m <sup>2</sup>
Office	3%	22 W/m <sup>2</sup>	0.66 W/m <sup>2</sup>
Corridor	10%	9.2 W/m <sup>2</sup>	0.92 W/m <sup>2</sup>
Weighted Average Post1980 Lowrise total lighting loads			4.96 W/m <sup>2</sup>

## Post-1980 Lowrise: Plug and Process Loads Comparison

Post-1980 Small Hotel			Post-1980 Midrise		
Space activity	Plug load	Source	Space activity	Plug load	Source
Hotel guest room	14.31 W/m <sup>2</sup>	[8]	Apartment	5.38 W/m <sup>2</sup>	[9]
Office	12.9 W/m <sup>2</sup>	[8]	Office	12.9 W/m <sup>2</sup>	[9]
Corridor	0	[8]	Corridor	0	[9]

## Post-1980 Lowrise: Plug and Process Loads Selection

Post-1980 Lowrise_Student Residence			
Space activity	Building area	Plug load from DOE models	Weighted Plug load
Student room	87%	9.85 W/m <sup>2</sup>	8.57 W/m <sup>2</sup>
Office	3%	12.9 W/m <sup>2</sup>	0.39 W/m <sup>2</sup>
Corridor	10%	0	0
Weighted Average Post1980 Low-rise total plug loads (including elevator)			8.95 W/m <sup>2</sup>
Weighted Average Post1980 Low-rise total plug loads (including elevator)			9 W/m <sup>2</sup>

\* Plug loads must add 1900 kWh/year for elevators

\* 1900kWh/365 day \* hours of use \* (1000 W/ 1kWh)/ Reference Area (m<sup>2</sup>)

\* (1900/365) \* (day/15.6 hours) \*(1000 W/ kW) \*(1/7428m<sup>2</sup>) = 0.045 W/m<sup>2</sup>

## Post-1980 Lowrise: Water System Comparison

Post-1980 Small Hotel			Post-1980 Midrise		
Space activity	DHW	Source	Space activity	DHW	Source
Hotel guest room	0.2 L/h/m <sup>2</sup>	[8]	Apartment	0.15 L/h/m <sup>2</sup>	[9]
Office	0		Office	0	
Corridor	0		Corridor	0	

## Post-1980 Lowrise: Water System Selection

Post-1980 Lowrise_Student Residence			
Space activity	Building area	DHW from DOE models	Weighted DHW
Student room	87%	0.20	0.175 L/h/m <sup>2</sup>

Office	3%	0	0
Corridor	10%	0	0
Weighted Average Pre1980 Low-rise total water system loads			0.19 L/h/m <sup>2</sup>

- \* Small Hotel water system loads are used to represent pre-1980 Lowrise student residence loads. The less efficient consumption was used for pre-1980 vintages.

## Post-1980 Lowrise: Equipment Comparison

Post-1980 Small Hotel		
Heating Type	Gas furnace, unit heater, PTAC electric heat	2003 CBECS
Cooling Type	DX	2003 CBECS
Fan Control	Constant	2003 CBECS
SWH Type	gas water heater	
Fuel	gas	
Cooling Efficiency	3.4	IDF Small Hotel input
Thermal Efficiency (%)	80	Winiarski and Halverson, 2008
Temperature Setpoint (°C)	60	

Post-1980 Midrise Apartment		
Heating Type	Gas furnace	90.1 Mechanical Subcommittee
Cooling Type	Split system DX	90.1 Mechanical Subcommittee
Fan Control	CAV	90.1 Mechanical Subcommittee
SWH Type	Gas water heater	
Fuel	gas	
Cooling Efficiency	3.4	IDF Midrise Apartment input
Thermal Efficiency (%)	78	Winiarski and Halverson, 2008
Temperature Setpoint (°C)	60	

## Post-1980 Lowrise: Equipment Selection

Post-1980 Lowrise student residence	
Heating Type	Gas furnace
Cooling Type	Split system DX
Fan Control	CAV
SWH Type	gas water heater
Fuel	gas
Cooling Efficiency	3.4
Thermal Efficiency (%)	78
Temperature Setpoint (°C)	60

- \* The models will have a 21°C for both heating and cooling year around.
- \* Equipment COP will be set .78 for heating, and 3.4 for cooling (Post1980 Small Hotel and Midrise).
- \* No economizer
- \* No natural ventilation is assigned

Post-1980 Lowrise: Schedule Selection

Occupancy Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	87%	1	1	1	1	1	1	1	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.3	0.52	0.87	0.87	1	1	1	1
DOE Midrise	Office	3%	0	0	0	0	0	0	0	0	1	1	1	1	0.5	1	1	1	1	0	0	0	0	0	0	0
DOE Small H	BLDG_OCC_SCH	10%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.5	0.7	0.7	0.8	0.9	0.9	0.9
DOE Midrise	Apartment_wknd	87%	1	1	1	1	1	1	1	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.3	0.52	0.87	0.87	1	1	1	1
DOE Midrise	Office_WKND	3%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DOE Small H	BLDG_OCC_SCH_WKND	10%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.6	0.6	0.6	0.7	0.7	0.7

Lighting Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	68%	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.6	0.8	1.0	1.0	0.7	0.4	0.2
DOE Midrise	Corridor	19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DOE Midrise	Office_Ltg_Sch_Base	13%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE Midrise	Apartment_WKND	68%	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.6	0.8	1.0	1.0	0.7	0.4	0.2
DOE Midrise	Corridor_WKND	19%	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DOE Midrise	Office_Ltg_Sch_Base_WKND	13%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Plug and Process Loads Schedules																										
Source	Schedule name	Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DOE Midrise	Apartment	92%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.7	0.69	0.66	0.65	0.68	0.8	1	1	0.93	0.89	0.85	0.71	0.58
DOE Midrise	Office	8%	0.33	0.33	0.33	0.33	0.33	0.38	0.38	0.43	0.43	0.43	1	1	0.94	1	1	1	1	0.75	0.63	0.63	0.48	0.48	0.33	0.33
DOE Midrise	Apartment	92%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.7	0.69	0.66	0.65	0.68	0.8	1	1	0.93	0.89	0.85	0.71	0.58
DOE Midrise	Office	8%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Domestic Hot Water																										
DOE Small H	GuestRoom_SWH_Sch	100%	0.2	0.15	0.15	0.15	0.2	0.35	0.6	0.8	0.55	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.55	0.4	0.4	0.6	0.45	0.25
DOE Small H	GuestRoom_SWH_Sch_WKND	100%	0.2	0.15	0.15	0.15	0.2	0.35	0.6	0.8	0.55	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.55	0.4	0.4	0.6	0.45	0.25

- \* Occupancy schedules: area weighted based on activity use percentages
- \* Lighting schedules: Area weighted average based on lighting density percentages. Space activities with highest LPD contribution to total lighting loads (W/m²) were used to define the whole building schedules.
- \* Plug and process schedules: Area weighted average based on plug and process load percentages.
- \* Domestic Hot Water: Area weighted average based on DHW percentages.

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[5] ASHRAE Standard 62.1-2004 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[6] ASHRAE Standard 62-1999 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[7] ASHRAE Standard 90.1-1989, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[8] PNNL - 17875 Technical Support Document: The Development of the Advanced Energy Design Guide for Highway Lodging Buildings

[9] DOE Commercial Reference Building Report

## Post-1980 Midrise: Form Comparison

Building form variables	Large Hotel	Highrise Apartment	Midrise
Vintage	Post 1980	2004	Post 1980
Total conditioned area	11,345 m <sup>2</sup>	7836 m <sup>2</sup>	13474 m <sup>2</sup>
Number of floors	6 + basement	10	7
Building height	22 m	30.5 m	21 m
Aspect Ratio	5.1	2.75	n/a
Window to wall ratio	30%	30%	30%
Shading	None	None	n/a
Ground floor to ceiling height	3.96 m	3.05m	n/a
Floor to floor height	3.05 m	3.05m	n/a
Building shape	Rectangle	Rectangle	n/a
Source	[1]	[2]	[3]

## Post-1980 Midrise: Form Selection

Post-1980 Midrise_student residence		
Characterization inputs	Reference Method	Wireframe Method
Total conditioned area	13474 m <sup>2</sup>	GIS/DaftLogic defined
Number of floors	7	DaftLogic defined
Building height	21 m	GIS/DaftLogic defined
Aspect Ratio*	3.9	GIS/DaftLogic defined
Window to wall ratio*	30%	30%
Shading	None	None
Floor to floor height*	3 m	3m
Building shape	Rectangle	GIS defined

\* The Average aspect ratio of the DOE Large Hotel and Highrise Apartment is considered

\* Window-to-wall ratio of 30% was defined as this ratio was common in student residence buildings

\*Floor-to-floor height was set as 3m in all categories.

## Post-1980 Midrise: Fabric Comparison

Post 1980 Large Hotel		2004 Highrise Apartment
<b>Ground floor slab</b>		
Name	ext-slab	Typical Insulated Carpeted 6in Slab Floor
Layer 1	HW CONCRETE	6 in. Normalweight Concrete floor
Layer 2	CP02 CARPET PAD	Typical Carpet Pad
R-value	0.54 m <sup>2</sup> *K/W	m <sup>2</sup> *K/W
<b>Ceiling</b>		
Name	INT-FLOOR-UNDERSIDE	Typical Interior Ceiling
Layer 1	CP02 CARPET PAD	CP02 CARPET PAD
Layer 2	MAT-CC05 4 HW CONCRETE	100mm Normalweight concrete floor
<b>Exterior roof</b>		
Name	IEAD Res Roof	Typical IEAD Roof R-15.87
Layer 1	Roof Membrane	Roof Membrane
Layer 2	IEAD Res Roof Insulation	Typical Insulation R-14.76
Layer 3	Metal decking	Metal Roof Surface
R-value	3.97 m <sup>2</sup> *K/W	2.79 m <sup>2</sup> *K/W
<b>Exterior wall</b>		
Name	Mass Res Ext Wall	Typical Insulated Steel Framed Exterior Wall
Layer 1	1IN Stucco	25mm Stucco
Layer 2	8IN Concrete HW	5/8in. Gypsum Board
Layer 3	Mass Res Wall Insulation	Typical Insulation R-13.45
R-value	1/2 IN Gypsum	5/8in. Gypsum Board
<b>Interior wall</b>		
Name	Int-walls	Typical Interior Wall
Layer 1	1/2IN Gypsum	1/2IN Gypsum
Layer 2	1/2IN Gypsum	1/2IN Gypsum
<b>Interior floor</b>		
Name	INT-FLOOR-TOPSIDE	Typical Interior Floor
Layer 1	MAT-CC05 4 HW CONCRETE	100mm Normalweight concrete floor
Layer 2	CP02 CARPET PAD	CP02 CARPET PAD
<b>Glazing System</b>		
Name	Window Res Fixed	U 0.62 SHGC 0.39Dbl Blue 6mm/6mm Air
Layer 1	Res Fixed Assembly Window	Blue 6mm – Air 6mm – Clear 6mm
U-Factor	2.95 W/m <sup>2</sup> *K	1.95 W/ m <sup>2</sup> *K
<b>Internal mass</b>		
Name	Interior Furnishings	Interior Furnishings
Layer 1	Standard Wood 6inch	Standard Wood 6inch
Source	[1]	[2]

## Post-1980 Midrise: Fabric Selection

Post-1980 Midrise student residence		
Component name	Assembly name	Assembly details
Ground floor slab	ext-slab	0.54 m <sup>2</sup> *K/W
Exterior roof	IEAD Res Roof	3.97 m <sup>2</sup> *K/W
Exterior wall	Mass Res Ext Wall	2.48 m <sup>2</sup> *K/W
Ceiling	INT-FLOOR-UNDERSIDE	-
Interior walls	Int-walls	-
Interior floor	INT-FLOOR-TOPSIDE	-
Internal mass	Interior Furnishings	-
Glazing system	U-Factor	2.95 W/ m <sup>2</sup> *K
	SHGC	0.39
	Visible transmittance	0.31
Air tightness	ACH@75Pa	0.6

## Post-1980 Midrise: Space Activity Comparison

Pitman Hall		Large Hotel		Highrise Apartment	
Space Activity	Area	Space Activity	Area	Space Activity	Area
Administrative offices	1%	Basement	17%	Apartment	87%
Common use	6%	Retail	1%	Corridor	10%
Food services	3%	Mechanical	1%	Office	3%
Residence living	43%	Storage	1%		
Residence service	4%	Laundry	1%		
Washrooms	2%	Cafe	2%		
Corridors	20%	Lobby	12%		
Non- assignable space	10%	Corridor	17%		
Parking structure	11%	Dining	3%		
		Banquet	3%		
		Kitchen	1%		
		Guest room	41%		
Source	[4]		[1]		[2]

## Post-1980 Midrise: Space Activity Selection

Post-1980 Midrise_Student Residence	
Space Activity	Area
Student dormitory	45%
Corridors	20%
Office space	5%
Lobby	5%
Kitchen	5%
Banquet/Cafe	8%



Basement	10%
Washrooms	2%

## Post-1980 Midrise: Occupancy Comparison

Post-1980 Large Hotel				2004 Highrise Apartment			
Space activity	Occupancy per space	Occupancy density	Source	Space activity	Occupancy per space	Occupancy density	Source
Guest room	1.5 pax	26 m <sup>2</sup> /pax	[1]	Apartment	2.5 pax	35.3 m <sup>2</sup> /pax	[1]
Lobby	422 pax	3 m <sup>2</sup> /pax	[1]	Office	2 pax	44 m <sup>2</sup> /pax	[1]
Kitchen	6 pax	18.5 m <sup>2</sup> /pax	[1]				
Banquet	238 pax	1.4 m <sup>2</sup> /pax	[1]				
Cafe	135 pax	1.4 m <sup>2</sup> /pax	[1]				
Basement	53 pax	37.1 m <sup>2</sup> /pax	[1]				
Washroom	21 pax	10 m <sup>2</sup> /pax	[2]				

## Post-1980 Midrise: Occupancy Selection

Post-1980 Midrise_Student Residence			
Space activity	Building area	Occupancy from DOE models	Weighted Occupancy
Student dormitory	45%	26 m <sup>2</sup> /pax	11.7 m <sup>2</sup> /pax
Office	5%	44 m <sup>2</sup> /pax	2.2 m <sup>2</sup> /pax
Corridor	20%	0 m <sup>2</sup> /pax	0.0 m <sup>2</sup> /pax
Lobby	5%	3 m <sup>2</sup> /pax	0.2 m <sup>2</sup> /pax
Kitchen	5%	18.5 m <sup>2</sup> /pax	0.9 m <sup>2</sup> /pax
Banquet/Cafe	8%	1.4 m <sup>2</sup> /pax	0.1 m <sup>2</sup> /pax
Basement	10%	37.1 m <sup>2</sup> /pax	3.7 m <sup>2</sup> /pax
Washroom	2%	10 m <sup>2</sup> /pax	0.2 m <sup>2</sup> /pax
Weighted Average Post-1980 Midrise total peak occupant density			32 m <sup>2</sup> /pax

## Post-1980 Midrise: Ventilation Rate Comparison

Post-1980 Large Hotel			2004 Highrise		
Space activity	Outdoor air	Source	Space activity	Outdoor air	Source
Guest room	0.36 L/s/m <sup>2</sup>	[3]	Apartment	0.29 L/s/m <sup>2</sup>	[3]
Corridor	0.25 L/s/m <sup>2</sup>	[3]	Office	0.51 L/s/m <sup>2</sup>	[3]
Lobby	0.9 L/s/m <sup>2</sup>	[3]	Corridor	0.25 L/s/m <sup>2</sup>	[3]
Kitchen	0.43 L/s/m <sup>2</sup>	[3]			
Banquet	7.17 L/s/m <sup>2</sup>	[3]			
Café	7.17 L/s/m <sup>2</sup>	[3]			
Basement	0.25 L/s/m <sup>2</sup>	[3]			
Washroom	1.4 L/s/m <sup>2</sup>	[3]			

## Post-1980 Midrise: Ventilation Rate Selection

Post-1980 Midrise_Student Residence			
Space activity	Building area	Outdoor air from DOE models	Weighted Outdoor air
Student dormitory	45%	0.36 L/s/m <sup>2</sup>	0.16 L/s/m <sup>2</sup>
Office	5%	0.508 L/s/m <sup>2</sup>	0.03 L/s/m <sup>2</sup>
Corridor	20%	0.25 L/s/m <sup>2</sup>	0.05 L/s/m <sup>2</sup>
Lobby	5%	0.89 L/s/m <sup>2</sup>	0.04 L/s/m <sup>2</sup>
Kitchen	5%	0.43 L/s/m <sup>2</sup>	0.02 L/s/m <sup>2</sup>
Banquet/Cafe	8%	7.17 L/s/m <sup>2</sup>	0.57 L/s/m <sup>2</sup>
Basement	10%	0.25 L/s/m <sup>2</sup>	0.03 L/s/m <sup>2</sup>
Washroom	2%	1.4 L/s/m <sup>2</sup>	0.03 L/s/m <sup>2</sup>
Weighted Average Post1980 Midrise total ventilation rate			0.93 L/s/m <sup>2</sup>

## Post-1980 Midrise: Lighting Power Density Comparison

Post-1980 Large Hotel			2004 Highrise		
Space activity	Lights	Source	Space activity	Lights	Source
Guest room	19.1 W/m <sup>2</sup>	[4]	Apartment	3.76 W/m <sup>2</sup>	[5]
Corridor	13.08 W/m <sup>2</sup>	[4]	Office	11.8 W/m <sup>2</sup>	[5]
Lobby	20.29 W/m <sup>2</sup>	[4]	Corridor	5.9 W/m <sup>2</sup>	[5]
Kitchen	16.83 W/m <sup>2</sup>	[4]			
Banquet	27.56 W/m <sup>2</sup>	[4]			
Café	15.74 W/m <sup>2</sup>	[4]			
Basement	7.53 W/m <sup>2</sup>	[4]			
Washroom	9.61 W/m <sup>2</sup>	[4]			

## Post-1980 Midrise: Lighting Power Density Selection

Post-1980 Midrise Lighting Power Density			
Space activity	Building area	Lights from DOE models	Weighted Lights
Guest room	45%	3.76 W/m <sup>2</sup>	1.69 W/m <sup>2</sup>
Corridor	5%	11.8 W/m <sup>2</sup>	0.59 W/m <sup>2</sup>
Lobby	20%	13.08 W/m <sup>2</sup>	2.61 W/m <sup>2</sup>
Kitchen	5%	20.29 W/m <sup>2</sup>	1.01 W/m <sup>2</sup>
Banquet	5%	16.83 W/m <sup>2</sup>	0.84 W/m <sup>2</sup>
Café	8%	21.65 W/m <sup>2</sup>	1.73 W/m <sup>2</sup>
Basement	10%	7.53 W/m <sup>2</sup>	0.75 W/m <sup>2</sup>
Washroom	2%	9.61 W/m <sup>2</sup>	0.19 W/m <sup>2</sup>
Weighted Average Post1980 Midrise total lighting loads			9.43 W/m <sup>2</sup>

## Post-1980 Midrise: Plug and Process Loads Comparison

Post-1980 Large Hotel			2004 Highrise		
Space activity	Plug load	Source	Space activity	Plug load	Source
Guest room	14 W/m <sup>2</sup>	[6-7]	Apartment	6.73	[8]
Corridor	0 W/m <sup>2</sup>	[6-7]	Office	6.73	[8]
Lobby	8.07 W/m <sup>2</sup>	[6-7]	Corridor	0	[8]
Kitchen	127 W/m <sup>2</sup>	[6-7]			
Banquet	67.84 W/m <sup>2</sup>	[6-7]			
Café	5.38 W/m <sup>2</sup>	[6-7]			
Basement	5.38 W/m <sup>2</sup>	[6-7]			
Washroom	4 W/m <sup>2</sup>	[6-7]			

## Post-1980 Midrise: Plug and Process Loads Selection

Post-1980 Midrise Student Residence			
Space activity	Building area	Plug load from DOE models	Weighted Plug load
Student dormitory	45%	10.37 W/m <sup>2</sup>	4.66 W/m <sup>2</sup>
Office	5%	6.73 W/m <sup>2</sup>	0.34 W/m <sup>2</sup>
Corridor	20%	0 W/m <sup>2</sup>	0.00 W/m <sup>2</sup>
Lobby	5%	8.07 W/m <sup>2</sup>	0.40 W/m <sup>2</sup>
Kitchen	5%	127 W/m <sup>2</sup>	6.35 W/m <sup>2</sup>
Banquet/Cafe	8%	26.43 W/m <sup>2</sup>	2.11 W/m <sup>2</sup>
Basement	10%	5.38 W/m <sup>2</sup>	0.54 W/m <sup>2</sup>
Washroom	2%	4 W/m <sup>2</sup>	0.08 W/m <sup>2</sup>
Weighted Average Post1980 Midrise total plug loads (including elevator)			14.49 W/m <sup>2</sup>

\* Plug loads must add 4161 kWh/year for elevators

\* 4161 kWh/365 day \* hours of use \* (1000 W/ 1kWh)/ Reference Area (m<sup>2</sup>)

\* (4161/365) \* (day/15.6 hours) \*(1000 W/ kW) \*(1/11,213m<sup>2</sup>) = 0.10 W/m<sup>2</sup>

## Post-1980 Midrise: Water System Comparison

Post-1980 Large Hotel			2004 Highrise Apartment		
Space activity	DHW	Source	Space activity	DHW	Source
Guest room	0.2 L/h/m <sup>2</sup>	[6-7]	Apartment	0.15 L/h/m <sup>2</sup>	[8]
Corridor	0		Office	0	
Lobby	0		Corridor	0	
Kitchen	1.62 L/h/m <sup>2</sup>	[6-7]			
Banquet	0				
Café	0				
Basement	0				
Washroom	0.3 L/h/m <sup>2</sup>	[6-7]			

## Post-1980 Midrise: Water System Selection

Post-1980 Midrise_Student Residence			
Space activity	Building area	DHW from DOE models	Weighted DHW
Student dormitory	45%	0.20 L/h/m <sup>2</sup>	0.09 L/h/m <sup>2</sup>
Kitchen	5%	1.62 L/h/m <sup>2</sup>	0.08 L/h/m <sup>2</sup>
Washroom	2%	0.3 L/h/m <sup>2</sup>	0.01 L/h/m <sup>2</sup>
Weighted Average Post1980 Midrise total water system loads			0.18 L/h/m <sup>2</sup>

## Post-1980 Midrise: Equipment Comparison

Post-1980 Large Hotel			
Heating Type	Gas furnace, unit heater, PTAC electric heat	2003 CBECS	
Cooling Type	DX	2003 CBECS	
Fan Control	Constant	2003 CBECS	
SWH Type	gas water heater		
Fuel	gas		
Cooling Efficiency	3.4	IDF Small Hotel input	
Thermal Efficiency (%)	80	Winiarski and Halverson, 2008	
Temperature Setpoint (°C)	60		

2004 Highrise Apartment			
Heating Type	Water source heat pumps	90.1 Mechanical Subcommittee	
Cooling Type		90.1 Mechanical Subcommittee	
Fan Control	Constant Volume	90.1 Mechanical Subcommittee	
SWH Type	Central water heater with storage tank		
Fuel	Natural gas		
Cooling Efficiency	3.4	IDF Highrise Apartment input	
Thermal Efficiency (%)	80	Requirements in code	
Temperature Setpoint (°C)	60		

## Post-1980 Midrise: Equipment Selection

Post-1980 Midrise student residence		
Heating Type	Gas boiler	
Cooling Type	2 air cooled chillers	
Fan Control	CAV	
SWH Type	gas water heater	
Fuel	gas	
Cooling Efficiency	3.4	
Thermal Efficiency (%)	80	
Temperature Setpoint (°C)	60	

\* No economizer

\* No natural ventilation is assigned

## Post-1980 Midrise: Schedule Selection

Occupancy Schedules																										
Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Highrise	Apartment	45%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.30	0.52	0.87	0.87	0.87	1.00	1.00	1.00
Large Hotel	Lobby	5%	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.7	0.7	0.7	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.2	0.2	0.2	0.2	0.1	0.1
Large Hotel	BLDG_OCC_SCH	50%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.5	0.7	0.7	0.8	0.9	0.9	0.9
2004 Highrise	Apartment_WKND	45%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.30	0.52	0.87	0.87	0.87	1.00	1.00	1.00
Large Hotel	Lobby_WKND	5%	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.7	0.7	0.7	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Large Hotel	BLDG_OCC_SCH_WKND	50%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.6	0.6	0.6	0.7	0.7	0.7

## Lighting Schedules

[illegible]

## Plug and Process Loads Schedules

Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Highrise	Apartment	32%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.70	0.69	0.66	0.65	0.68	0.80	1.00	1.00	0.93	0.89	0.85	0.71	0.58
2004 Highrise	Office	2%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
2004 Highrise	Office	2%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.50	1.00	1.00	1.00	1.00	0.94	0.59	0.66	0.65	0.80	1.00	1.00	0.93	0.89	0.85	0.71	
Large Hotel	Kitchen	44%	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.35	0.35	0.25	0.35	0.35	0.35	0.25	0.25	0.25	0.35	0.35	0.35	0.25	0.25	0.25	0.25	
Large Hotel	BLDG_EQUID_SCH	22%	0.3	0.25	0.2	0.2	0.2	0.3	0.5	0.6	0.5	0.5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.7	0.9	0.95	0.9	0.7	
2004 Highrise	Apartment	32%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.70	0.69	0.66	0.65	0.68	0.80	1.00	1.00	0.93	0.89	0.85	0.71	
2004 Highrise	Office	2%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
Large Hotel	Kitchen-WKND	44%	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.3	
Large Hotel	BLDG_EQUID_SCH_WKND	22%	0.3	0.3	0.2	0.2	0.2	0.2	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.7	0.8	0.8	0.8	0.7	

## Domestic Hot Water

Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Highrise	Apartment	51%	0.08	0.04	0.01	0.04	0.27	0.94	1.00	0.96	0.84	0.76	0.61	0.53	0.47	0.41	0.47	0.55	0.73	0.86	0.82	0.75	0.61	0.53	0.29	
Large Hotel	Kitchen	46%	0.2	0.15	0.15	0.2	0.25	0.5	0.6	0.55	0.45	0.4	0.45	0.4	0.35	0.3	0.3	0.4	0.55	0.6	0.5	0.55	0.45	0.25		
Secondary	Showers_SVH_SCH	3%	0	0	0	0	0	0	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	0	0	0	0		
2004 Highrise	Apartment	51%	0.08	0.04	0.01	0.04	0.27	0.94	1.00	0.96	0.84	0.76	0.61	0.53	0.47	0.41	0.47	0.55	0.73	0.86	0.82	0.75	0.61	0.53	0.29	
Large Hotel	Kitchen_VIKIND	46%	0.25	0.2	0.2	0.2	0.3	0.5	0.5	0.5	0.55	0.5	0.5	0.4	0.4	0.3	0.3	0.4	0.5	0.5	0.4	0.5	0.4	0.2		
Secondary	Showers_SVH_SCH	3%	0	0	0	0	0	0	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	0	0	0	0		

- \* Occupancy schedules: area weighted based on activity use percentages
- \* Lighting schedules: Area weighted average based on lighting density percentages. Space activities with highest LPD contribution to total lighting loads ( $\text{W/m}^2$ ) were used to define the whole building schedules.
- \* Plug and process schedules: Area weighted average based on plug and process load percentages.
- \* Domestic Hot Water: Area weighted average based on DHW percentages.

## Post-1980 Midrise: Sources

[1] 2003 CBECS Data

[2] PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York

[3] Mandatory Energy Reports 2013 – Ontario, Daft Logic, Visual Judgment, Geographical Information Systems, and the Architectural Conservancy of Ontario

[4] Ryerson Space Audit Data. URL: <https://ryerson.iwmsapp.com/archibus/>

[5] ASHRAE Standard 62.1-2004 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[6] ASHRAE Standard 62-1999 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[7] ASHRAE Standard 90.1-1989, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[8] PNNL - 17875 Technical Support Document: The Development of the Advanced Energy Design Guide for Highway Lodging Buildings

[9] DOE Commercial Reference Building Report

## Pre-1980 Highrise: Form Comparison

Building form variables	Large Hotel	Highrise Apartment	Highrise
Vintage	Pre-1980	2004	Pre-1980
Total conditioned area	11,345 m <sup>2</sup>	7836 m <sup>2</sup>	8396 m <sup>2</sup>
Number of floors	6 + basement	10	15
Building height	22 m	30.5 m	45 m
Aspect Ratio	5.1	2.75	n/a
Window to wall ratio	30%	30%	30%
Shading	None	None	None
Ground floor to ceiling height	3.96 m	3.05m	n/a
Floor to floor height	3.05 m	3.05m	n/a
Building shape	Rectangle	Rectangle	Tower
Source	[1]	[2]	[3]

## Pre-1980 Highrise: Form Selection

Post-1980 Highrise Student Residence		
Characterization inputs	Reference Method	Wireframe Method
Total conditioned area	8396 m <sup>2</sup>	GIS/DaftLogic defined
Number of floors	15	DaftLogic defined
Building height	45 m	GIS/DaftLogic defined
Aspect Ratio*	3.9	GIS/DaftLogic defined
Window to wall ratio*	30%	30%
Shading	None	None
Floor to floor height*	3 m	3m
Building shape	Rectangle	GIS defined

\* The Average aspect ratio of the DOE Large Hotel and Highrise Apartment is considered

\* Window-to-wall ratio of 30% was defined as this ratio was common in student residence buildings

\*Floor-to-floor height was set as 3m in all categories.

## Pre-1980 Highrise: Fabric Comparison

Pre-1980 Large Hotel		2004 Highrise Apartment
<b>Ground floor slab</b>		
Name	ext-slab	Typical Insulated Carpeted 6in Slab Floor
Layer 1	HW CONCRETE	6 in. Normalweight Concrete floor
Layer 2	CP02 CARPET PAD	Typical Carpet Pad
R-value	0.54 m <sup>2</sup> *K/W	m <sup>2</sup> *K/W
<b>Ceiling</b>		
Name	INT-FLOOR-UNDERSIDE	Typical Interior Ceiling
Layer 1	CP02 CARPET PAD	CP02 CARPET PAD
Layer 2	MAT-CC05 4 HW CONCRETE	100mm Normalweight concrete floor
<b>Exterior roof</b>		
Name	Typical IEAD Roof R-16.67	Typical IEAD Roof R-15.87
Layer 1	Roof Membrane	Roof Membrane
Layer 2	IEAD Res Roof Insulation R15.55	Typical Insulation R-14.76
Layer 3	Metal Roof Surface	Metal Roof Surface
R-value	2.99 m <sup>2</sup> *K/W	2.79 m <sup>2</sup> *K/W
<b>Exterior wall</b>		
Name	TYPICAL INSULATED EXTERIOR MASS WALL R-6.9	Typical Insulated Steel Framed Exterior Wall
Layer 1	1 IN Stucco	25mm Stucco
Layer 2	8in CONCRETE HW Ref Bldg	5/8in. Gypsum Board
Layer 3	Typical Insulation R-4.51	Typical Insulation R-13.45
R-value	1/2 IN Gypsum	5/8in. Gypsum Board
<b>Interior wall</b>		
Name	Typical Interior Wall	Typical Interior Wall
Layer 1	G01 13mm gypsum board	1/2IN Gypsum
Layer 2	G01 13mm gypsum board	1/2IN Gypsum
<b>Interior floor</b>		
Name	Typical Interior Floor	Typical Interior Floor
Layer 1	100mm Normalweight concrete floor	100mm Normalweight concrete floor
Layer 2	CP02 CARPET PAD	CP02 CARPET PAD
<b>Glazing System</b>		
Name	U 0.62 SHGC 0.41 Simple Glazing Window	U 0.62 SHGC 0.39Dbl Blue 6mm/6mm Air
Layer 1	U 0.62 SHGC 0.41 Simple Glazing	Blue 6mm – Air 6mm – Clear 6mm
U-Factor	3.53 W/m <sup>2</sup> *K	1.95 W/ m <sup>2</sup> *K
<b>Internal mass</b>		
Name	Interior Furnishings	Interior Furnishings
Layer 1	Standard Wood 6inch	Standard Wood 6inch
Source	[1]	[2]



## Pre-1980 Highrise: Fabric Selection

Pre-1980 Highrise student residence		
Component name	Assembly name	Assembly details
Ground floor slab	ext-slab	0.54 m <sup>2</sup> *K/W
Exterior roof	IEAD Res Roof	2.9 m <sup>2</sup> *K/W
Exterior wall	Mass Res Ext Wall	1.22 m <sup>2</sup> *K/W
Ceiling	INT-FLOOR-UNDERSIDE	-
Interior walls	Int-walls	-
Interior floor	INT-FLOOR-TOPSIDE	-
Internal mass	Interior Furnishings	-
Glazing system	U-Factor	3.53 W/ m <sup>2</sup> *K
	SHGC	0.41
	Visible transmittance	0.32
Air tightness	ACH@75Pa	0.6

## Pre-1980 Highrise: Space Activity Comparison

Pitman Hall		Large Hotel		Highrise Apartment	
Space Activity	Area	Space Activity	Area	Space Activity	Area
Administrative offices	1%	Basement	17%	Apartment	87%
Common use	6%	Retail	1%	Corridor	10%
Food services	3%	Mechanical	1%	Office	3%
Residence living	43%	Storage	1%		
Residence service	4%	Laundry	1%		
Washrooms	2%	Cafe	2%		
Corridors	20%	Lobby	12%		
Non- assignable space	10%	Corridor	17%		
Parking structure	11%	Dining	3%		
		Banquet	3%		
		Kitchen	1%		
		Guest room	41%		
Source	[4]		[1]		[2]

## Pre-1980 Highrise: Space Activity Selection

Pre-1980 Highrise Student Residence	
Space Activity	Area
Student dormitory	50%
Corridors	18%
Office space	5%
Lobby	2%
Kitchen	3%
Banquet/Cafe	10%

Basement	8%
Washrooms	4%

## Pre-1980 Highrise: Occupancy Comparison

Pre-1980 Large Hotel				2004 Highrise Apartment			
Space activity	Occupancy per space	Occupancy density	Source	Space activity	Occupancy per space	Occupancy density	Source
Guest room	1.5 pax	26 m <sup>2</sup> /pax	[1]	Apartment	2.5 pax	35.3 m <sup>2</sup> /pax	[1]
Lobby	422 pax	3 m <sup>2</sup> /pax	[1]	Office	2 pax	44 m <sup>2</sup> /pax	[1]
Kitchen	6 pax	18.5 m <sup>2</sup> /pax	[1]				
Banquet	238 pax	1.4 m <sup>2</sup> /pax	[1]				
Cafe	135 pax	1.4 m <sup>2</sup> /pax	[1]				
Basement	53 pax	37.1 m <sup>2</sup> /pax	[1]				
Washroom	21 pax	10 m <sup>2</sup> /pax	[2]				

## Pre-1980 Highrise: Occupancy Selection

Pre-1980 Highrise Student Residence			
Space activity	Building area	Occupancy from DOE models	Weighted Average Occupancy
Student dormitory	50%	26 m <sup>2</sup> /pax	13 m <sup>2</sup> /pax
Office	5%	44 m <sup>2</sup> /pax	2.2 m <sup>2</sup> /pax
Corridor	18%	0	0
Lobby	2%	3 m <sup>2</sup> /pax	0.1 m <sup>2</sup> /pax
Kitchen	3%	18.5 m <sup>2</sup> /pax	0.6 m <sup>2</sup> /pax
Banquet/Cafe	10%	1.4 m <sup>2</sup> /pax	0.1 m <sup>2</sup> /pax
Basement	8%	37.1 m <sup>2</sup> /pax	3 m <sup>2</sup> /pax
Washroom	4%	10 m <sup>2</sup> /pax	0.4 m <sup>2</sup> /pax
Pre-1980 Highrise total peak occupancy density			19 m <sup>2</sup> /pax

## Pre-1980 Highrise: Ventilation Rate Comparison

Pre-1980 Large Hotel			2004 Highrise		
Space activity	Outdoor air	Source	Space activity	Outdoor air	Source
Guest room	0.36 L/s/m <sup>2</sup>	[3]	Apartment	0.29 L/s/m <sup>2</sup>	[3]
Corridor	0.25 L/s/m <sup>2</sup>	[3]	Office	0.51 L/s/m <sup>2</sup>	[3]
Lobby	0.9 L/s/m <sup>2</sup>	[3]	Corridor	0.25 L/s/m <sup>2</sup>	[3]
Kitchen	0.43 L/s/m <sup>2</sup>	[3]			
Banquet	7.17 L/s/m <sup>2</sup>	[3]			
Café	7.17 L/s/m <sup>2</sup>	[3]			
Basement	0.25 L/s/m <sup>2</sup>	[3]			
Washroom	1.4 L/s/m <sup>2</sup>	[3]			

## Pre-1980 Highrise: Ventilation Rate Selection

Pre-1980 Highrise Student Residence			
Space activity	Building area	Outdoor air from DOE models	Weighted Outdoor air
Student dormitory	50%	13 L/s/pax	6.50 L/s/pax
Office	5%	9 L/s/pax	0.45 L/s/pax
Corridor	18%	0	0
Lobby	2%	10 L/s/pax	0.20 L/s/pax
Kitchen	3%	8 L/s/pax	0.25 L/s/pax
Banquet/Cafe	10%	10 L/s/pax	1.00 L/s/pax
Basement	8%	9 L/s/pax	0.75 L/s/pax
Washroom	4%	14 L/s/pax	0.56 L/s/pax
Weighted Average Post1980 Midrise total ventilation rate			9.7 L/s/pax

## Pre-1980 Highrise: Lighting Power Density Comparison

Pre-1980 Large Hotel			2004 Highrise		
Space activity	Lights	Source	Space activity	Lights	Source
Guest room	19.1 W/m <sup>2</sup>	[4]	Apartment	3.76 W/m <sup>2</sup>	[5]
Corridor	13.08 W/m <sup>2</sup>	[4]	Office	11.8 W/m <sup>2</sup>	[5]
Lobby	20.29 W/m <sup>2</sup>	[4]	Corridor	5.9 W/m <sup>2</sup>	[5]
Kitchen	16.83 W/m <sup>2</sup>	[4]			
Banquet	27.56 W/m <sup>2</sup>	[4]			
Café	15.74 W/m <sup>2</sup>	[4]			
Basement	7.53 W/m <sup>2</sup>	[4]			
Washroom	9.61 W/m <sup>2</sup>	[4]			

## Pre-1980 Highrise: Lighting Power Density Selection

Pre-1980 Highrise Lighting Power Density			
Space activity	Building area	Lights from DOE models	Weighted Lights
Guest room	50%	11.43 W/m <sup>2</sup>	5.72 W/m <sup>2</sup>
Corridor	5%	11.8 W/m <sup>2</sup>	0.59 W/m <sup>2</sup>
Lobby	18%	13.08 W/m <sup>2</sup>	2.35 W/m <sup>2</sup>
Kitchen	2%	20.29 W/m <sup>2</sup>	0.41 W/m <sup>2</sup>
Banquet	3%	16.83 W/m <sup>2</sup>	0.50 W/m <sup>2</sup>
Café	10%	21.65 W/m <sup>2</sup>	2.17 W/m <sup>2</sup>
Basement	8%	7.53 W/m <sup>2</sup>	0.60 W/m <sup>2</sup>
Washroom	4%	9.61 W/m <sup>2</sup>	0.38 W/m <sup>2</sup>
Weighted Average Post1980 Midrise total lighting loads			12.72 W/m <sup>2</sup>

## Pre-1980 Highrise: Plug and Process Loads Comparison

Pre-1980 Large Hotel			2004 Highrise		
Space activity	Plug load	Source	Space activity	Plug load	Source
Guest room	14 W/m <sup>2</sup>	[6-7]	Apartment	6.73	[8]
Corridor	0 W/m <sup>2</sup>	[6-7]	Office	6.73	[8]
Lobby	8.07 W/m <sup>2</sup>	[6-7]	Corridor	0	[8]
Kitchen	127 W/m <sup>2</sup>	[6-7]			
Banquet	67.84 W/m <sup>2</sup>	[6-7]			
Café	5.38 W/m <sup>2</sup>	[6-7]			
Basement	5.38 W/m <sup>2</sup>	[6-7]			
Washroom	4 W/m <sup>2</sup>	[6-7]			

## Pre-1980 Highrise: Plug and Process Loads Selection

Pre-1980 Highrise Student Residence			
Space activity	Building area	Plug load from DOE models	Weighted Plug load
Student dormitory	50%	14.00	7.00
Office	5%	6.73	0.34
Corridor	18%	0	0.00
Lobby	2%	8.07	0.16
Kitchen	3%	127.00	3.81
Banquet/Cafe	10%	26.43	2.64
Basement	8%	5.38	0.43
Washroom	4%	4	0.16
			14.54 W/m <sup>2</sup>
Weighted Average Pre1980 Highrise total plug loads (including elevator)			14.63 W/m <sup>2</sup>

\* Plug loads must add 4161 kWh/year for elevators

\* 4161 kWh/365 day \* hours of use \* (1000 W/ 1kWh)/ Reference Area (m<sup>2</sup>)

\* (4161/365) \* (day/15.6 hours) \*(1000 W/ kW) \*(1/11,213m<sup>2</sup>) = 0.10 W/m<sup>2</sup>

## Pre-1980 Highrise: Water System Comparison

Pre-1980 Large Hotel			2004 Highrise Apartment		
Space activity	DHW	Source	Space activity	DHW	Source
Guest room	0.2 L/h/m <sup>2</sup>	[6-7]	Apartment	0.15 L/h/m <sup>2</sup>	[8]
Corridor	0		Office	0	
Lobby	0		Corridor	0	
Kitchen	1.62 L/h/m <sup>2</sup>	[6-7]			
Banquet	0				
Café	0				
Basement	0				
Washroom	0.3 L/h/m <sup>2</sup>	[6-7]			

## Pre-1980 Highrise: Water System Selection

Pre-1980 Highrise Student Residence			
Space activity	Building area	DHW from DOE models	Weighted DHW
Student dormitory	50%	0.20 L/h/m <sup>2</sup>	0.10 L/h/m <sup>2</sup>
Kitchen	3%	1.62 L/h/m <sup>2</sup>	0.05 L/h/m <sup>2</sup>
Washroom	4%	0.3 L/h/m <sup>2</sup>	0.01 L/h/m <sup>2</sup>
Weighted Average Pre-1980 Highrise total water system loads			0.16 L/h/m <sup>2</sup>

## Pre-1980 Highrise: Equipment Comparison

Pre-1980 Large Hotel			
Heating Type	FCU in rooms, CV ventilation, MZCAV in common areas		2003 CBECS
Cooling Type	2 air cooled chillers		2003 CBECS
Fan Control	Constant		2003 CBECS
SWH Type	Gas boiler		
Fuel	Natural gas		
Cooling Efficiency	Requirements in codes or standards		IDF Small Hotel input
Thermal Efficiency (%)	78		Winiarski and Halverson, 2008
Temperature Setpoint (°C)	60		

2004 Highrise Apartment			
Heating Type	Water source heat pumps	90.1 Mechanical Subcommittee	
Cooling Type		90.1 Mechanical Subcommittee	
Fan Control	Constant Volume	90.1 Mechanical Subcommittee	
SWH Type	Central water heater with storage tank		
Fuel	Natural gas		
Cooling Efficiency	3.4	IDF Highrise Apartment input	
Thermal Efficiency (%)	80	Requirements in code	
Temperature Setpoint (°C)	60		

## Pre-1980 Highrise: Equipment Selection

Pre-1980 Highrise Student residence	
Heating Type	Gas boiler
Cooling Type	2 air cooled chillers
Fan Control	CAV
SWH Type	gas water heater
Fuel	gas
Cooling Efficiency	3.4
Thermal Efficiency (%)	78
Temperature Setpoint (°C)	60

\* No economizer

\* No natural ventilation is assigned

## Pre-1980 Highrise: Schedule Selection

Occupancy Schedules																										
Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Highrise	Apartment	50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.30	0.52	0.87	0.87	0.87	1.00	1.00	1.00
	Large Hotel Lobby	2%	0.1	0.1	0.1	0.1	0.1	0.3	0.7	0.7	0.7	0.7	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.2	0.2	0.2	0.2	0.1	0.1
Large Hotel	BLDG_OCC_SCH	48%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.5	0.5	0.7	0.7	0.8	0.9	0.9
2004 Highrise	Apartment _ WKNKD	50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.39	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.30	0.52	0.87	0.87	0.87	1.00	1.00	1.00
Large Hotel	Lobby _ WKNKD	2%	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.7	0.7	0.7	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Large Hotel	BLDG_OCC_SCH _ WKNKD	48%	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.5	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.6	0.6	0.6	0.7	0.7	0.7

## Lighting Schedules

[illegible]

## Plug and Process Loads Schedules

Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Hgpnise Apartment		48%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.70	0.69	0.66	0.65	0.68	0.80	1.00	1.00	0.93	0.89	0.85	0.71	0.58
2004 Hgpnise Office		2%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
Large Hotel	Kitchen	26%	0.1	0.1	0.1	0.1	0.1	0.1	0.25	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.25	0.25	0.25	0.25	
Large Hotel	Bldg Equip SCH	24%	0.3	0.25	0.2	0.2	0.2	0.3	0.5	0.6	0.5	0.5	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.7	0.9	0.95	0.9	0.7	0.4	
2004 Hgpnise Apartment		48%	0.45	0.41	0.39	0.38	0.38	0.43	0.54	0.65	0.66	0.67	0.69	0.70	0.69	0.66	0.65	0.68	0.80	1.00	1.00	0.93	0.89	0.85	0.71	0.58
2004 Hgpnise Office		2%	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
Large Hotel	Kitchen-WKND	26%	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
Large Hotel	Bldg Equip SCH WKND	24%	0.3	0.3	0.2	0.2	0.2	0.2	0.4	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.7	0.8	0.8	0.7	0.4	

## Domestic Hot Water

Source	Schedule name	Area	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	Noon	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 pm
2004 Hignise	Apartment	62%	0.08	0.04	0.01	0.01	0.04	0.27	0.94	1.00	0.96	0.84	0.76	0.61	0.53	0.47	0.41	0.47	0.55	0.73	0.86	0.82	0.75	0.61	0.53	0.29
Large Hotel	Kitchen	30%	0.2	0.15	0.15	0.15	0.2	0.25	0.5	0.6	0.55	0.45	0.4	0.45	0.4	0.35	0.3	0.3	0.3	0.4	0.55	0.6	0.5	0.55	0.45	0.25
Secondary	Showers_SWH_SCH	7%	0	0	0	0	0	0	0	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.5	1	1	1	0	0	0	0	0
2004 Hignise	Apartment	62%	0.08	0.04	0.01	0.01	0.04	0.27	0.94	1.00	0.96	0.84	0.76	0.61	0.53	0.47	0.41	0.47	0.55	0.73	0.86	0.82	0.75	0.61	0.53	0.29
Large Hotel	Kitchen_WXND	30%	0.25	0.2	0.2	0.2	0.2	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.5	0.4	0.5	0.4	0.2
Secondary	Showers_SWH_SCH	7%	0	0	0	0	0	0	0	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.5	1	1	1	0	0	0	0	0

- \* Occupancy schedules: area weighted based on activity use percentages
- \* Lighting schedules: Area weighted average based on lighting density percentages. Space activities with highest LPD contribution to total lighting loads ( $\text{W}/\text{m}^2$ ) were used to define the whole building schedules.
- \* Plug and process schedules: Area weighted average based on plug and process load percentages.
- \* Domestic Hot Water: Area weighted average based on DHW percentages.

## Pre-1980 Highrise: Sources

[1] 2003 CBECS Data

[2] PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York

[3] Mandatory Energy Reports 2013 – Ontario, Daft Logic, Visual Judgment, Geographical Information Systems, and the Architectural Conservancy of Ontario

[4] Ryerson Space Audit Data. URL: <https://ryerson.iwmsapp.com/archibus/>

[5] ASHRAE Standard 62.1-2004 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[6] ASHRAE Standard 62-1999 Table 6-1, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[7] ASHRAE Standard 90.1-1989, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[8] PNNL - 17875 Technical Support Document: The Development of the Advanced Energy Design Guide for Highway Lodging Buildings

[9] DOE Commercial Reference Building Report

## **Appendix C:** Reference Building Model Characterization Templates



## Pre-1980 Lowrise: Characterization Templates Before Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Constructions	Pre1980_Low-rise					
Loads	B_Res_0 loads					
Conditioning	Pre1980 Low-rise_Conditioning					
Ventilation	Pre1980 Low-rise_Ventilation					
Domestic hot water	Pre1980Low-rise_DHW					
Daylight mesh resolution					1	m
Daylight workplane height					0.8	m
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area					1	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
People	<input checked="" type="checkbox"/>					
Occupancy density	0.03125				p/m2	
Occupancy schedule	B_Res_Y_Occ_Pre1980 Lowrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	9.01				W/m2	
Equipment availability schedule	B_Res_Y_Plg_Pre1980 Lowrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	11.4				W/m2	
Lighting availability schedule	B_Res_Y_Lgt pre1980 Lowrise					
Dimming type	Off					
Illuminance target	200				lux	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw_Pre1980 Lowrise					
Supply temperature	60				degC	
Inlet temperature	16				degC	
Flow rate	0.000175				m3/h/m2	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value			Units		
Facade	Insulated Steel Framed Exterior Wall R7					
Ground	ext-slab-mass					
Partition	Typical interior wall					
Roof	Typical IEAD Roof R17					
Slab	Typical interior floor					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value			Units		
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21			degC		
Heating schedule	B_Res_Y_Het					
Heating limit type	NoLimit					
Max heating capacity	200			W/m2		
Max heat flow	100			m3/s/m2		
Heating CoP	0.8					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21			degC		
Cooling schedule	B_Res_Y_Col					
Cooling limit type	NoLimit					
Max cooling capacity	100			W/m2		
Max cool flow	100			m3/s/m2		
Cooling CoP	3.4					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	AllOn					
Min fresh air per area	0.00045			m3/s/m2		
Min fresh air per person	0			m3/s/p		
Economizer type	NoEconomizer					
Heat recovery type	None					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.92	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	U 0.62 SHGC 0.41 Simple Glazing					
Operable area	0.5					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input checked="" type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Pre-1980 Lowrise: Characterization Templates After Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Constructions	Pre1980_Low-rise					
Loads	B_Res_0 loads					
Conditioning	Pre1980 Low-rise_Conditioning					
Ventilation	Pre1980 Low-rise_Ventilation					
Domestic hot water	Pre1980Low-rise_DHW					
Daylight mesh resolution					1	m
Daylight workplane height					0.8	m
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area					1	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
People	<input checked="" type="checkbox"/>					
Occupancy density	0.03125				p/m2	
Occupancy schedule	B_Res_Y_Occ_Pre1980 Lowrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	9.01				W/m2	
Equipment availability schedule	B_Res_Y_Plug_Pre1980 Lowrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	11.4				W/m2	
Lighting availability schedule	B_Res_Y_Lgt pre1980 Lowrise					
Dimming type	Off					
Illuminance target	200				lux	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw_Pre1980 Lowrise					
Supply temperature	60				degC	
Inlet temperature	16				degC	
Flow rate	0.00019				m3/h/m2	

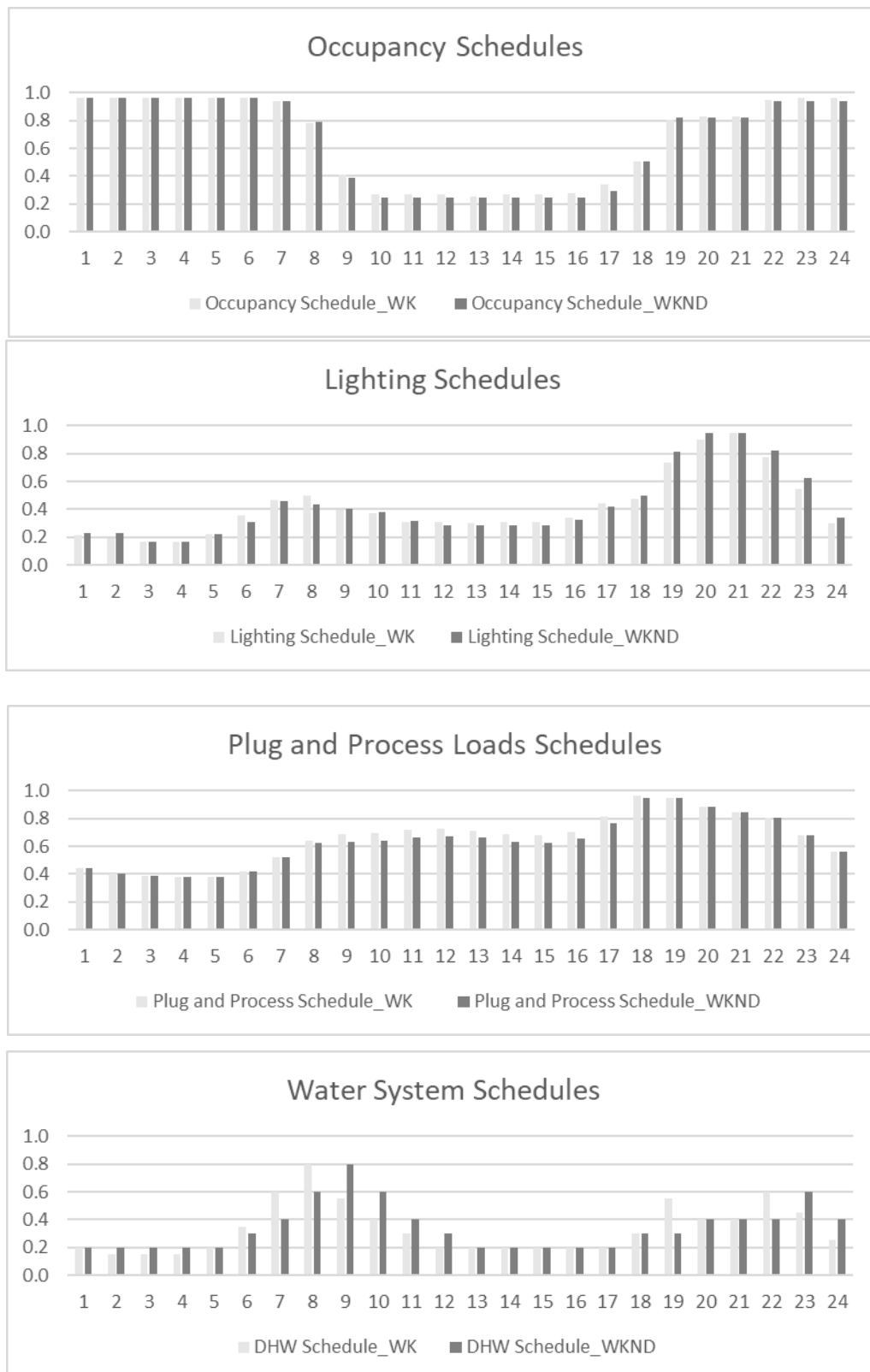
Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value			Units		
Facade	Insulated Steel Framed Exterior Wall R7 ▾					
Ground	ext-slab-mass ▾					
Partition	Typical interior wall ▾					
Roof	Typical IEAD Roof R17 ▾					
Slab	Typical interior floor ▾					
Facade is adiabatic				<input type="checkbox"/>		
Ground is adiabatic				<input type="checkbox"/>		
Partition is adiabatic				<input type="checkbox"/>		
Roof is adiabatic				<input type="checkbox"/>		

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21		degC			
Heating schedule	B_Res_Y_Het ▾					
Heating limit type	NoLimit ▾					
Max heating capacity	200		W/m2			
Max heat flow	100		m3/s/m2			
Heating CoP	0.8					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21		degC			
Cooling schedule	B_Res_Y_Col ▾					
Cooling limit type	NoLimit ▾					
Max cooling capacity	100		W/m2			
Max cool flow	100		m3/s/m2			
Cooling CoP	3.4					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	AllOn ▾					
Min fresh air per area	0.00045		m3/s/m2			
Min fresh air per person	0		m3/s/p			
Economizer type	NoEconomizer ▾					
Heat recovery type	None ▾					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.92	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	U 0.62 SHGC 0.41 Simple Glazing					
Operable area	0.5					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input checked="" type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Pre-1980 Lowrise: Daily Schedules



## Post-1980 Lowrise: Characterization Templates Before Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Constructions	Post1980_Low-rise					
Loads	B_Res_0 loads					
Conditioning	Post1980 Low-rise_Conditioning					
Ventilation	Post1980 Low-rise_Ventilation					
Domestic hot water	Post1980Low-rise_DHW					
Daylight mesh resolution	1				m	
Daylight workplane height	0.8				m	
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area	1					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
People	<input checked="" type="checkbox"/>					
Occupancy density	0.03125				p/m2	
Occupancy schedule	B_Res_Y_Occ_post1980 Lowrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	9				W/m2	
Equipment availability schedule	B_Res_Y_Plg-post1980 Lowrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	4.96				W/m2	
Lighting availability schedule	B_Res_Y_Lgt_post1980 Lowrise					
Dimming type	Off					
Illuminance target	200				lux	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw_post1980 Lowrise					
Supply temperature	60				degC	
Inlet temperature	16				degC	
Flow rate	0.00017				m3/h/m2	



Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Facade	Steel Frame Res Ext Wall ▾					
Ground	ext-slab ▾					
Partition	Int-walls ▾					
Roof	IEAD Res Roof ▾					
Slab	INT-FLOOR-TOPSIDE ▾					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21	degC				
Heating schedule	B_Res_Y_Het ▾					
Heating limit type	NoLimit ▾					
Max heating capacity	200	W/m2				
Max heat flow	100	m3/s/m2				
Heating CoP	0.78					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21	degC				
Cooling schedule	B_Res_Y_Col ▾					
Cooling limit type	NoLimit ▾					
Max cooling capacity	150	W/m2				
Max cool flow	100	m3/s/m2				
Cooling CoP	3.4					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	AllOn ▾					
Min fresh air per area	0.00045	m3/s/m2				
Min fresh air per person	0	m3/s/p				
Economizer type	NoEconomizer ▾					
Heat recovery type	None ▾					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting		Value		Units		
Infiltration		<input checked="" type="checkbox"/>				
Infiltration rate		0.92	ACH			
Natural ventilation		<input type="checkbox"/>				
Nat vent min outdoor air temp		18	degC			
Nat vent max outdoor air temp		26	degC			
Nat vent max rel humidity		80				
Nat vent schedule		B_Res_Y_Nat				
Nat vent zone temperature setpoint		22	degC			
Scheduled ventilation		<input type="checkbox"/>				
Scheduled ventilation ACH		0.6	ACH			
Scheduled ventilation schedule		B_Res_Y_Nat				
Scheduled ventilation setpoint		22	degC			
Buoyancy		<input checked="" type="checkbox"/>				
Wind		<input checked="" type="checkbox"/>				

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting		Value		Units		
Type		External				
Construction		Window Res Operable				
Operable area		0				
Shading is used		<input type="checkbox"/>				
Shading system availability schedule		B_Res_Y_Occ				
Shading system setpoint		0.5	W/m2			
Shading system transmittance		0.5				
Shading system type		InteriorShade				
Zone mixing		<input checked="" type="checkbox"/>				
Zone mixing availability schedule		B_Res_Y_Occ				
Zone mixing delta temperature		2				
Zone mixing flow rate		0.001	m3/2			
Virtual partition		<input type="checkbox"/>				
Airflow network discharge coefficient		0.65				
Airflow network temperature setpoint		20	degC			

## Post-1980 Lowrise: Characterization Templates After Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Constructions	Post1980_Low-rise					
Loads	B_Res_0 loads					
Conditioning	Post1980 Low-rise_Conditioning					
Ventilation	Post1980 Low-rise_Ventilation					
Domestic hot water	Post1980Low-rise_DHW					
Daylight mesh resolution	1		m			
Daylight workplane height	0.8		m			
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area	1					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
People	<input checked="" type="checkbox"/>					
Occupancy density	0.03125		p/m2			
Occupancy schedule	B_Res_Y_Occ_post1980 Lowrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	10		W/m2			
Equipment availability schedule	B_Res_Y_Plg-post1980 Lowrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	7		W/m2			
Lighting availability schedule	B_Res_Y_Lgt_post1980 Lowrise					
Dimming type	Off					
Illuminance target	200		lux			

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw_post1980 Lowrise					
Supply temperature	60		degC			
Inlet temperature	16		degC			
Flow rate	0.0002		m3/h/m2			

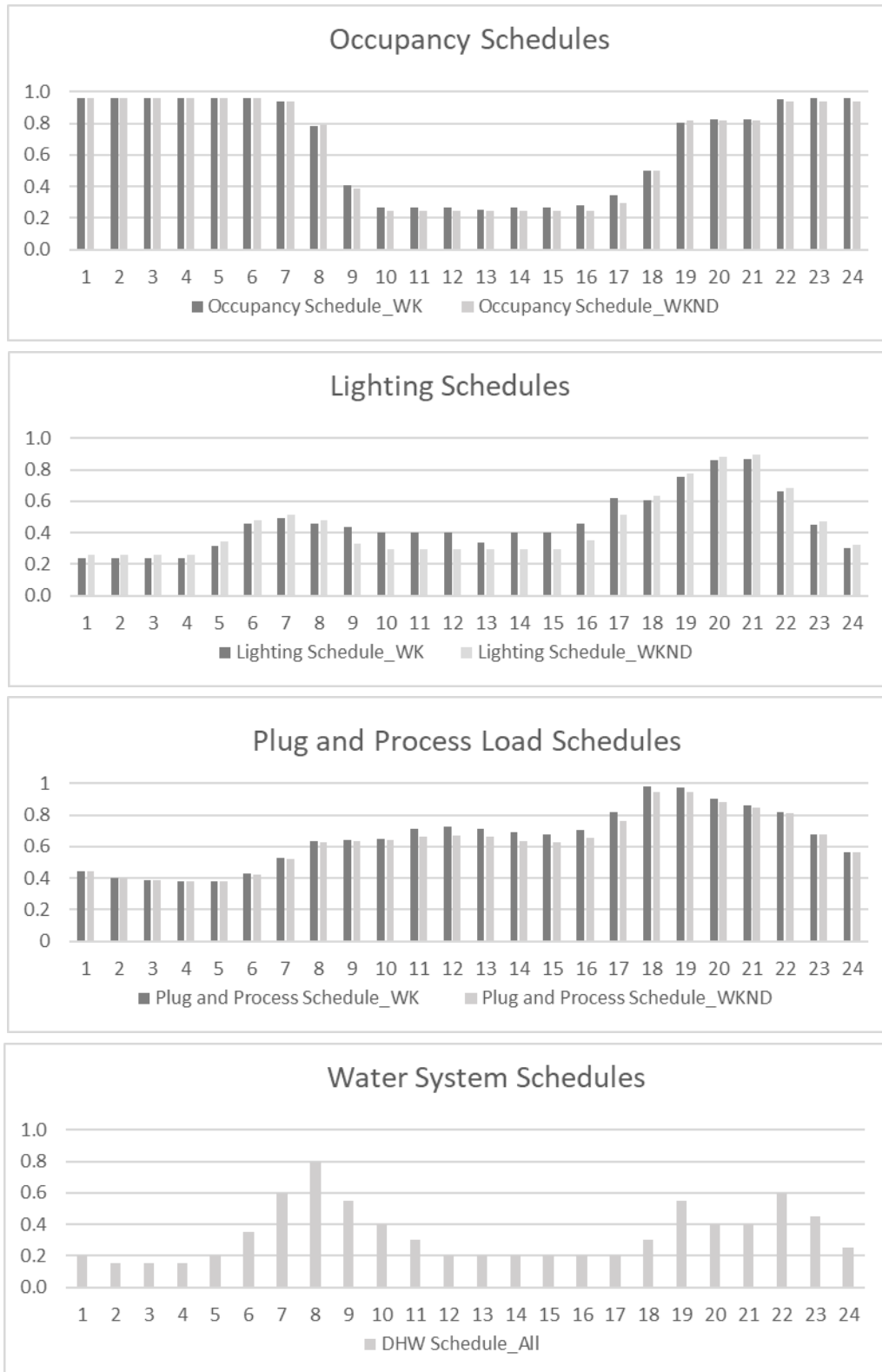
Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Facade	Steel Frame Res Ext Wall ▾					
Ground	ext-slab ▾					
Partition	Int-walls ▾					
Roof	IEAD Res Roof ▾					
Slab	INT-FLOOR-TOPSIDE ▾					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21		degC			
Heating schedule	B_Res_Y_Het ▾					
Heating limit type	NoLimit ▾					
Max heating capacity	200		W/m2			
Max heat flow	100		m3/s/m2			
Heating CoP	0.84					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21		degC			
Cooling schedule	B_Res_Y_Col ▾					
Cooling limit type	NoLimit ▾					
Max cooling capacity	150		W/m2			
Max cool flow	100		m3/s/m2			
Cooling CoP	3.4					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	AllOn ▾					
Min fresh air per area	0.00045		m3/s/m2			
Min fresh air per person	0		m3/s/p			
Economizer type	NoEconomizer ▾					
Heat recovery type	None ▾					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.92	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	Window Res Operable					
Operable area	0					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input checked="" type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Post-1980 Lowrise: Daily Schedules



## Post-1980 Midrise: Characterization Templates Before Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Constructions	Post1980_Mid-rise Construction ▾					
Loads	B_Res_Post1980-Midrise ▾					
Conditioning	Post1980 Mid-rise_Conditioning ▾					
Ventilation	Post1980 Low-rise_Ventilation ▾					
Domestic hot water	Post1980Mid-rise_DHW ▾					
Daylight mesh resolution	1				m	
Daylight workplane height	0.8				m	
Internal mass construction	Std Wood 6inch ▾					
Internal mass exposed per floor area	1					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
People	<input checked="" type="checkbox"/>					
Occupancy density	0.053				p/m2	
Occupancy schedule	B_Res_Y_Occ post1980Midrise ▾					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	14.58				W/m2	
Equipment availability schedule	B_Res_Y_Plg post-1980 Mid-rise ▾					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	9.43				W/m2	
Lighting availability schedule	B_Res_Y_Lgt post1980 Midrise ▾					
Dimming type	Off ▾					
Illuminance target	200				lux	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw post1980 Mid-rise ▾					
Supply temperature	60				degC	
Inlet temperature	16				degC	
Flow rate	0.00017				m3/h/m2	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Facade	Mass Res Ext Wall ▾					
Ground	ext-slab ▾					
Partition	Int-walls ▾					
Roof	IEAD Res Roof ▾					
Slab	INT-FLOOR-TOPSIDE ▾					
Facade is adiabatic			<input type="checkbox"/>			
Ground is adiabatic			<input type="checkbox"/>			
Partition is adiabatic			<input type="checkbox"/>			
Roof is adiabatic			<input type="checkbox"/>			

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Heating			<input checked="" type="checkbox"/>			
Heating setpoint	21		degC			
Heating schedule	B_Res_Y_Het ▾					
Heating limit type	NoLimit ▾					
Max heating capacity	200		W/m2			
Max heat flow	100		m3/s/m2			
Heating CoP	0.8					
Cooling			<input checked="" type="checkbox"/>			
Cooling setpoint	21		degC			
Cooling schedule	B_Res_Y_Cooling ▾					
Cooling limit type	NoLimit ▾					
Max cooling capacity	300		W/m2			
Max cool flow	100		m3/s/m2			
Cooling CoP	3.4					
Mechanical ventilation			<input checked="" type="checkbox"/>			
Mechanical ventilation schedule	B_Res_Y_Occ post1980Midrise ▾					
Min fresh air per area	0		m3/s/m2			
Min fresh air per person	0.00922		m3/s/p			
Economizer type	NoEconomizer ▾					
Heat recovery type	None ▾					



Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.6	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	B_Dbl_Air_CI (6mm)					
Operable area	0					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Post-1980 Midrise: Characterization Templates After Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Constructions	Post1980_Mid-rise Construction ▾					
Loads	B_Res_Post1980-Midrise ▾					
Conditioning	Post1980 Mid-rise_Conditioning ▾					
Ventilation	Post1980 Low-rise_Ventilation ▾					
Domestic hot water	Post1980Mid-rise_DHW ▾					
Daylight mesh resolution					1 m	
Daylight workplane height					0.8 m	
Internal mass construction	Std Wood 6inch ▾					
Internal mass exposed per floor area					1	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
People	<input checked="" type="checkbox"/>					
Occupancy density	0.053				p/m2	
Occupancy schedule	B_Res_Y_Occ post1980Midrise ▾					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	18				W/m2	
Equipment availability schedule	B_Res_Y_Plg post-1980 Mid-rise ▾					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	13				W/m2	
Lighting availability schedule	B_Res_Y_Lgt post1980 Midrise ▾					
Dimming type	Off ▾					
Illuminance target	200				lux	

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value				Units	
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw post1980 Mid-rise ▾					
Supply temperature	60				degC	
Inlet temperature	16				degC	
Flow rate	0.0002				m3/h/m2	

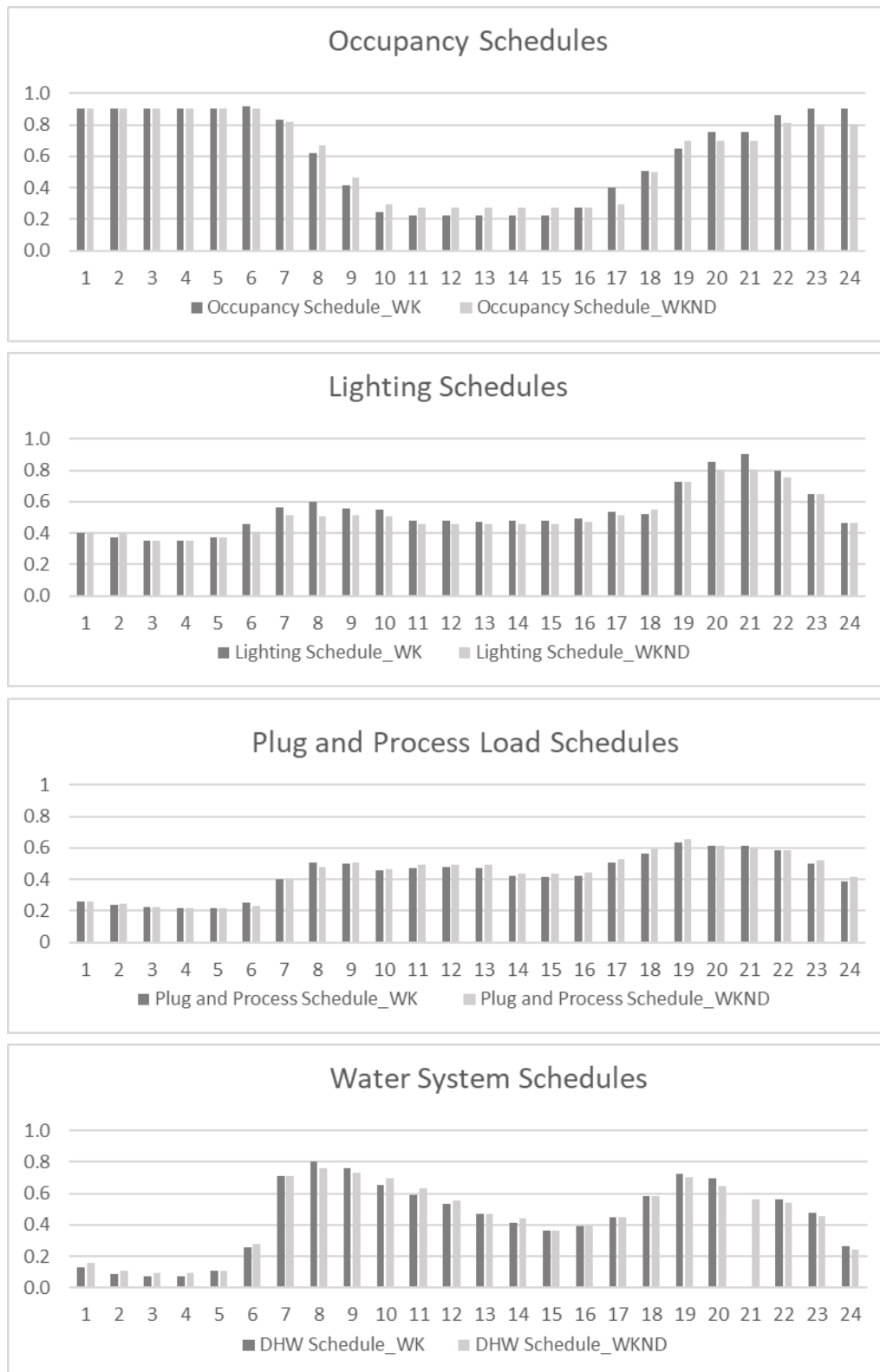
Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Facade	Mass Res Ext Wall					
Ground	ext-slab					
Partition	Int-walls					
Roof	IEAD Res Roof					
Slab	INT-FLOOR-TOPSIDE					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21	degC				
Heating schedule	B_Res_Y_Het					
Heating limit type	NoLimit					
Max heating capacity	200	W/m2				
Max heat flow	100	m3/s/m2				
Heating CoP	0.78					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21	degC				
Cooling schedule	B_Res_Y_Cooling					
Cooling limit type	NoLimit					
Max cooling capacity	300	W/m2				
Max cool flow	100	m3/s/m2				
Cooling CoP	2.5					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	B_Res_Y_Occ post1980Midrise					
Min fresh air per area	0	m3/s/m2				
Min fresh air per person	0.00922	m3/s/p				
Economizer type	NoEconomizer					
Heat recovery type	None					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.6	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	Window Res Fixed					
Operable area	0					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Post-1980 Midrise: Daily Schedules



## Pre-1980 Highrise: Characterization Templates Before Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Constructions	Pre1980_High-rise					
Loads	B_Res_pre1980 High-rise					
Conditioning	Pre1980 High-rise_Conditioning					
Ventilation	Pre1980 High-rise_Ventilation					
Domestic hot water	Pre1980 Highrise_DHW					
Daylight mesh resolution	1		m			
Daylight workplane height	0.8		m			
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area	1					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
People	<input checked="" type="checkbox"/>					
Occupancy density	0.052		p/m2			
Occupancy schedule	B_Res_Y_Occ pre1980 Highrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	14.63		W/m2			
Equipment availability schedule	B_Res_Y_Plg pre1980 Highrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	12.72		W/m2			
Lighting availability schedule	B_Res_Y_Lgt pre1980 Highrise					
Dimming type	Off					
Illuminance target	200		lux			

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw					
Supply temperature	60		degC			
Inlet temperature	16		degC			
Flow rate	0.00016		m3/h/m2			

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Facade	Typical Insulated Exterior Mass Wall R-6.9 ▾					
Ground	ext-slab-mass ▾					
Partition	Typical interior wall ▾					
Roof	Typical IEAD Roof R16.67 ▾					
Slab	Typical interior floor ▾					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21	degC				
Heating schedule	B_Res_Y_Het ▾					
Heating limit type	NoLimit ▾					
Max heating capacity	200	W/m2				
Max heat flow	100	m3/s/m2				
Heating CoP	0.78					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21	degC				
Cooling schedule	B_Res_Y_Col ▾					
Cooling limit type	NoLimit ▾					
Max cooling capacity	100	W/m2				
Max cool flow	100	m3/s/m2				
Cooling CoP	2.64					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	B_Res_Y_Occ pre1980 Highrise ▾					
Min fresh air per area	0.001	m3/s/m2				
Min fresh air per person	0.0097	m3/s/p				
Economizer type	NoEconomizer ▾					
Heat recovery type	None ▾					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting		Value		Units		
Infiltration		<input checked="" type="checkbox"/>				
Infiltration rate		0.6		ACH		
Natural ventilation		<input type="checkbox"/>				
Nat vent min outdoor air temp		18		degC		
Nat vent max outdoor air temp		26		degC		
Nat vent max rel humidity		80				
Nat vent schedule		B_Res_Y_Nat				
Nat vent zone temperature setpoint		22		degC		
Scheduled ventilation		<input type="checkbox"/>				
Scheduled ventilation ACH		0.6		ACH		
Scheduled ventilation schedule		B_Res_Y_Nat				
Scheduled ventilation setpoint		22		degC		
Buoyancy		<input checked="" type="checkbox"/>				
Wind		<input checked="" type="checkbox"/>				

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting		Value		Units		
Type		External				
Construction		U 0.62 SHGC 0.41 Simple Glazing				
Operable area		0.5				
Shading is used		<input type="checkbox"/>				
Shading system availability schedule		B_Res_Y_Occ				
Shading system setpoint		0.5		W/m2		
Shading system transmittance		0.5				
Shading system type		InteriorShade				
Zone mixing		<input checked="" type="checkbox"/>				
Zone mixing availability schedule		B_Res_Y_Occ				
Zone mixing delta temperature		2				
Zone mixing flow rate		0.001		m3/2		
Virtual partition		<input type="checkbox"/>				
Airflow network discharge coefficient		0.65				
Airflow network temperature setpoint		20		degC		



## Pre-1980 Highrise: Characterization Templates After Adjusting

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Constructions	Pre1980_High-rise					
Loads	B_Res_pre1980 High-rise					
Conditioning	Pre1980 High-rise_Conditioning					
Ventilation	Pre1980 High-rise_Ventilation					
Domestic hot water	Pre1980 Highrise_DHW					
Daylight mesh resolution	1		m			
Daylight workplane height	0.8		m			
Internal mass construction	Std Wood 6inch					
Internal mass exposed per floor area	1					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
People	<input checked="" type="checkbox"/>					
Occupancy density	0.052		p/m2			
Occupancy schedule	B_Res_Y_Occ pre1980 Highrise					
Equipment	<input checked="" type="checkbox"/>					
Equipment power density	18		W/m2			
Equipment availability schedule	B_Res_Y_Plg pre1980 Highrise					
Lighting	<input checked="" type="checkbox"/>					
Lighting power density	16		W/m2			
Lighting availability schedule	B_Res_Y_Lgt pre1980 Highrise					
Dimming type	Off					
Illuminance target	200		lux			

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value		Units			
Enabled	<input checked="" type="checkbox"/>					
Schedule	B_Res_Y_Dhw					
Supply temperature	60		degC			
Inlet temperature	16		degC			
Flow rate	0.00021		m3/h/m2			

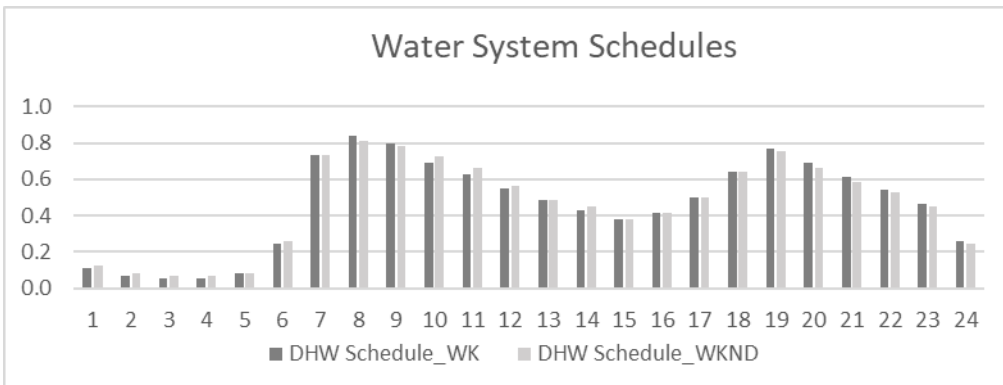
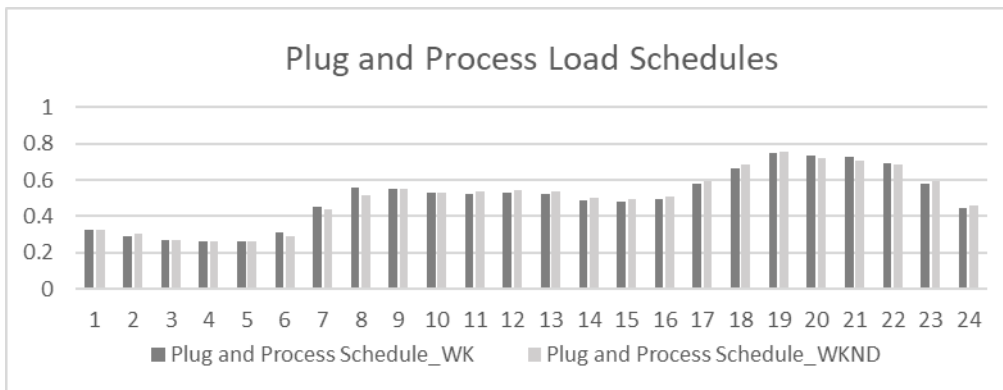
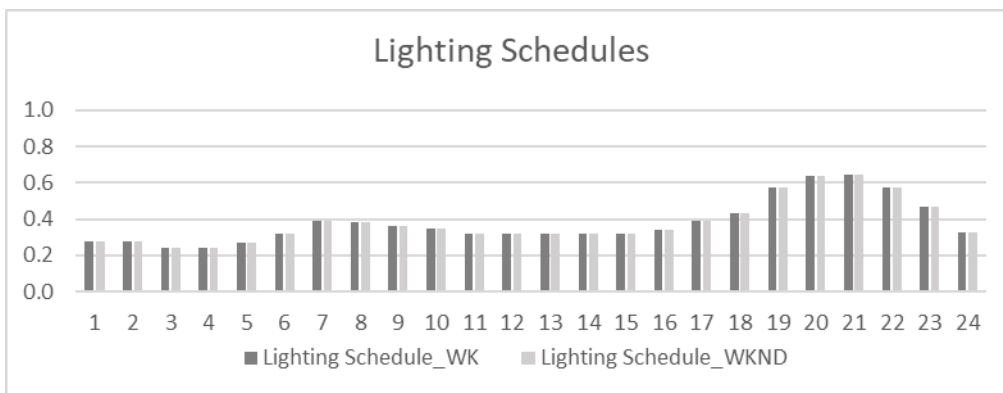
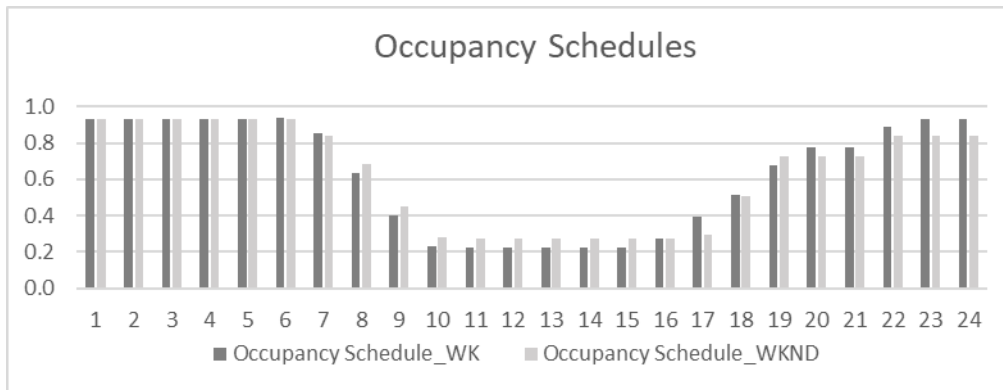
Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Facade	Typical Insulated Exterior Mass Wall R-6.9					
Ground	ext-slab-mass					
Partition	Typical interior wall					
Roof	Typical IEAD Roof R16.67					
Slab	Typical interior floor					
Facade is adiabatic	<input type="checkbox"/>					
Ground is adiabatic	<input type="checkbox"/>					
Partition is adiabatic	<input type="checkbox"/>					
Roof is adiabatic	<input type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Heating	<input checked="" type="checkbox"/>					
Heating setpoint	21	degC				
Heating schedule	B_Res_Y_Het					
Heating limit type	NoLimit					
Max heating capacity	200	W/m2				
Max heat flow	100	m3/s/m2				
Heating CoP	0.83					
Cooling	<input checked="" type="checkbox"/>					
Cooling setpoint	21	degC				
Cooling schedule	B_Res_Y_Col					
Cooling limit type	NoLimit					
Max cooling capacity	100	W/m2				
Max cool flow	100	m3/s/m2				
Cooling CoP	2.5					
Mechanical ventilation	<input checked="" type="checkbox"/>					
Mechanical ventilation schedule	B_Res_Y_Occ pre1980 Highrise					
Min fresh air per area	0.001	m3/s/m2				
Min fresh air per person	0.0097	m3/s/p				
Economizer type	NoEconomizer					
Heat recovery type	None					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Infiltration	<input checked="" type="checkbox"/>					
Infiltration rate	0.6	ACH				
Natural ventilation	<input type="checkbox"/>					
Nat vent min outdoor air temp	18	degC				
Nat vent max outdoor air temp	26	degC				
Nat vent max rel humidity	80					
Nat vent schedule	B_Res_Y_Nat					
Nat vent zone temperature setpoint	22	degC				
Scheduled ventilation	<input type="checkbox"/>					
Scheduled ventilation ACH	0.6	ACH				
Scheduled ventilation schedule	B_Res_Y_Nat					
Scheduled ventilation setpoint	22	degC				
Buoyancy	<input checked="" type="checkbox"/>					
Wind	<input checked="" type="checkbox"/>					

Zones	Loads	Constructions	Conditioning	Ventilation	Domestic Hot Water	Windows
Setting	Value	Units				
Type	External					
Construction	U 0.62 SHGC 0.41 Simple Glazing					
Operable area	0.5					
Shading is used	<input type="checkbox"/>					
Shading system availability schedule	B_Res_Y_Occ					
Shading system setpoint	0.5	W/m2				
Shading system transmittance	0.5					
Shading system type	InteriorShade					
Zone mixing	<input checked="" type="checkbox"/>					
Zone mixing availability schedule	B_Res_Y_Occ					
Zone mixing delta temperature	2					
Zone mixing flow rate	0.001	m3/2				
Virtual partition	<input type="checkbox"/>					
Airflow network discharge coefficient	0.65					
Airflow network temperature setpoint	20	degC				

## Pre-1980 Highrise: Daily Schedules



## **Appendix D:** Random Sampling in RStudio

```

# Random sampling of results
# Reading data into the files
setwd("C:/Users/Xavier/Desktop")
EUI <- read.csv('./EUI_Data.csv',header = TRUE, sep = ",",skip=0,stringsAsFactors=FALSE,colClasses = NA,na.strings = c("NA", ""))
Energy <- read.csv('./Energy_Data.csv',header = TRUE, sep = ",",skip=0,stringsAsFactors=FALSE,colClasses = NA,na.strings = c("NA", ""))

n=20
EUI_3=data.frame()
Energy_3=data.frame()
EUI_5=data.frame()
Energy_5=data.frame()
EUI_7=data.frame()
Energy_7=data.frame()
EUI_9=data.frame()
Energy_9=data.frame()
EUI_11=data.frame()
Energy_11=data.frame()
EUI_13=data.frame()
Energy_13=data.frame()
EUI_15=data.frame()
Energy_15=data.frame()
EUI_17=data.frame()
Energy_17=data.frame()
EUI_19=data.frame()
Energy_19=data.frame()

#Data Preparation & cleansing
# sets of 3
for (i in (1:n)) {
  EUI_sample_3 = EUI[sample(nrow(EUI), 3), ]
  Energy_sample_3 = Energy[sample(nrow(Energy), 3), ]
  EUI_3[1,i]= colSums(EUI_sample_3[1])
  EUI_3[2,i]= colSums(EUI_sample_3[2])
  EUI_3[3,i]= colSums(EUI_sample_3[3])
  #wireframe error
  EUI_3[4,i]=(EUI_3[1,i]-EUI_3[3,i])/EUI_3[3,i]
  #reference error
  EUI_3[5,i]=(EUI_3[2,i]-EUI_3[3,i])/EUI_3[3,i]
  Energy_3[1,i]= colSums(Energy_sample_3[1])
  Energy_3[2,i]= colSums(Energy_sample_3[2])
  Energy_3[3,i]= colSums(Energy_sample_3[3])
  #wireframe error
  Energy_3[4,i]=(Energy_3[1,i]-Energy_3[3,i])/Energy_3[3,i]
  #reference error
  Energy_3[5,i]=(Energy_3[2,i]-Energy_3[3,i])/Energy_3[3,i]
}

# sets of 5
for (i in (1:n)) {
  EUI_sample_5 = EUI[sample(nrow(EUI), 5), ]
  Energy_sample_5 = Energy[sample(nrow(Energy), 5), ]
  EUI_5[1,i]= colSums(EUI_sample_5[1])
  EUI_5[2,i]= colSums(EUI_sample_5[2])
  EUI_5[3,i]= colSums(EUI_sample_5[3])
  #wireframe error
  EUI_5[4,i]=(EUI_5[1,i]-EUI_5[3,i])/EUI_5[3,i]
  #reference error
  EUI_5[5,i]=(EUI_5[2,i]-EUI_5[3,i])/EUI_5[3,i]
  Energy_5[1,i]= colSums(Energy_sample_5[1])
  Energy_5[2,i]= colSums(Energy_sample_5[2])
  Energy_5[3,i]= colSums(Energy_sample_5[3])
  #wireframe error
  Energy_5[4,i]=(Energy_5[1,i]-Energy_5[3,i])/Energy_5[3,i]
  #reference error
  Energy_5[5,i]=(Energy_5[2,i]-Energy_5[3,i])/Energy_5[3,i]
}

# sets of 7
for (i in (1:n)) {
  EUI_sample_7 = EUI[sample(nrow(EUI), 7), ]
  Energy_sample_7 = Energy[sample(nrow(Energy), 7), ]
  EUI_7[1,i]= colSums(EUI_sample_7[1])
  EUI_7[2,i]= colSums(EUI_sample_7[2])
  EUI_7[3,i]= colSums(EUI_sample_7[3])
  #wireframe error
  EUI_7[4,i]=(EUI_7[1,i]-EUI_7[3,i])/EUI_7[3,i]
  #reference error
  EUI_7[5,i]=(EUI_7[2,i]-EUI_7[3,i])/EUI_7[3,i]
  Energy_7[1,i]= colSums(Energy_sample_7[1])
  Energy_7[2,i]= colSums(Energy_sample_7[2])
  Energy_7[3,i]= colSums(Energy_sample_7[3])
  #wireframe error
  Energy_7[4,i]=(Energy_7[1,i]-Energy_7[3,i])/Energy_7[3,i]
  #reference error
  Energy_7[5,i]=(Energy_7[2,i]-Energy_7[3,i])/Energy_7[3,i]
}

```

```

# sets of 9
for (i in (1:n)) {
  EUI_sample_9 = EUI[sample(nrow(EUI), 9), ]
  Energy_sample_9 = Energy[sample(nrow(Energy), 9), ]
  EUI_9[1,i] = colSums(EUI_sample_9[1])
  EUI_9[2,i] = colSums(EUI_sample_9[2])
  EUI_9[3,i] = colSums(EUI_sample_9[3])
  #wireframe error
  EUI_9[4,i] = (EUI_9[1,i] - EUI_9[3,i]) / EUI_9[3,i]
  #reference error
  EUI_9[5,i] = (EUI_9[2,i] - EUI_9[3,i]) / EUI_9[3,i]
  Energy_9[1,i] = colSums(Energy_sample_9[1])
  Energy_9[2,i] = colSums(Energy_sample_9[2])
  Energy_9[3,i] = colSums(Energy_sample_9[3])
  #wireframe error
  Energy_9[4,i] = (Energy_9[1,i] - Energy_9[3,i]) / Energy_9[3,i]
  #reference error
  Energy_9[5,i] = (Energy_9[2,i] - Energy_9[3,i]) / Energy_9[3,i]
}

#sets of 11
for (i in (1:n)) {
  EUI_sample_11 = EUI[sample(nrow(EUI), 11), ]
  Energy_sample_11 = Energy[sample(nrow(Energy), 11), ]
  EUI_11[1,i] = colSums(EUI_sample_11[1])
  EUI_11[2,i] = colSums(EUI_sample_11[2])
  EUI_11[3,i] = colSums(EUI_sample_11[3])
  #wireframe error
  EUI_11[4,i] = (EUI_11[1,i] - EUI_11[3,i]) / EUI_11[3,i]
  #reference error
  EUI_11[5,i] = (EUI_11[2,i] - EUI_11[3,i]) / EUI_11[3,i]
  Energy_11[1,i] = colSums(Energy_sample_11[1])
  Energy_11[2,i] = colSums(Energy_sample_11[2])
  Energy_11[3,i] = colSums(Energy_sample_11[3])
  #wireframe error
  Energy_11[4,i] = (Energy_11[1,i] - Energy_11[3,i]) / Energy_11[3,i]
  #reference error
  Energy_11[5,i] = (Energy_11[2,i] - Energy_11[3,i]) / Energy_11[3,i]
}

# sets of 13
for (i in (1:n)) {
  EUI_sample_13 = EUI[sample(nrow(EUI), 13), ]
  Energy_sample_13 = Energy[sample(nrow(Energy), 13), ]
  EUI_13[1,i] = colSums(EUI_sample_13[1])
  EUI_13[2,i] = colSums(EUI_sample_13[2])
  EUI_13[3,i] = colSums(EUI_sample_13[3])
  #wireframe error
  EUI_13[4,i] = (EUI_13[1,i] - EUI_13[3,i]) / EUI_13[3,i]
  #reference error
  EUI_13[5,i] = (EUI_13[2,i] - EUI_13[3,i]) / EUI_13[3,i]
  Energy_13[1,i] = colSums(Energy_sample_13[1])
  Energy_13[2,i] = colSums(Energy_sample_13[2])
  Energy_13[3,i] = colSums(Energy_sample_13[3])
  #wireframe error
  Energy_13[4,i] = (Energy_13[1,i] - Energy_13[3,i]) / Energy_13[3,i]
  #reference error
  Energy_13[5,i] = (Energy_13[2,i] - Energy_13[3,i]) / Energy_13[3,i]
}

#sets of 15
for (i in (1:n)) {
  EUI_sample_15 = EUI[sample(nrow(EUI), 15), ]
  Energy_sample_15 = Energy[sample(nrow(Energy), 15), ]
  EUI_15[1,i] = colSums(EUI_sample_15[1])
  EUI_15[2,i] = colSums(EUI_sample_15[2])
  EUI_15[3,i] = colSums(EUI_sample_15[3])
  #wireframe error
  EUI_15[4,i] = (EUI_15[1,i] - EUI_15[3,i]) / EUI_15[3,i]
  #reference error
  EUI_15[5,i] = (EUI_15[2,i] - EUI_15[3,i]) / EUI_15[3,i]
  Energy_15[1,i] = colSums(Energy_sample_15[1])
  Energy_15[2,i] = colSums(Energy_sample_15[2])
  Energy_15[3,i] = colSums(Energy_sample_15[3])
  #wireframe error
  Energy_15[4,i] = (Energy_15[1,i] - Energy_15[3,i]) / Energy_15[3,i]
  #reference error
  Energy_15[5,i] = (Energy_15[2,i] - Energy_15[3,i]) / Energy_15[3,i]
}

#sets of 17
for (i in (1:n)) {
  EUI_sample_17 = EUI[sample(nrow(EUI), 17), ]
  Energy_sample_17 = Energy[sample(nrow(Energy), 17), ]
  EUI_17[1,i] = colSums(EUI_sample_17[1])
  EUI_17[2,i] = colSums(EUI_sample_17[2])
  EUI_17[3,i] = colSums(EUI_sample_17[3])
  #wireframe error
  EUI_17[4,i] = (EUI_17[1,i] - EUI_17[3,i]) / EUI_17[3,i]
  #reference error
  EUI_17[5,i] = (EUI_17[2,i] - EUI_17[3,i]) / EUI_17[3,i]
  Energy_17[1,i] = colSums(Energy_sample_17[1])
  Energy_17[2,i] = colSums(Energy_sample_17[2])
  Energy_17[3,i] = colSums(Energy_sample_17[3])
  #wireframe error
  Energy_17[4,i] = (Energy_17[1,i] - Energy_17[3,i]) / Energy_17[3,i]
  #reference error
  Energy_17[5,i] = (Energy_17[2,i] - Energy_17[3,i]) / Energy_17[3,i]
}

# sets of 19
for (i in (1:n)) {
  EUI_sample_19 = EUI[sample(nrow(EUI), 19), ]
  Energy_sample_19 = Energy[sample(nrow(Energy), 19), ]
  EUI_19[1,i] = colSums(EUI_sample_19[1])
  EUI_19[2,i] = colSums(EUI_sample_19[2])
  EUI_19[3,i] = colSums(EUI_sample_19[3])
  #wireframe error
  EUI_19[4,i] = (EUI_19[1,i] - EUI_19[3,i]) / EUI_19[3,i]

```

```

#reference error
EUI_19[5,i]=(EUI_19[2,i]-EUI_19[3,i])/EUI_19[3,i]
Energy_19[1,i]= colSums (Energy_sample_19[1])
Energy_19[2,i]= colSums (Energy_sample_19[2])
Energy_19[3,i]= colSums (Energy_sample_19[3])
#wireframe error
Energy_19[4,i]=(Energy_19[1,i]-Energy_19[3,i])/Energy_19[3,i]
#reference error
Energy_19[5,i]=(Energy_19[2,i]-Energy_19[3,i])/Energy_19[3,i]
}

EUI3T=t(EUI_3)
EUI5T=t(EUI_5)
EUI7T=t(EUI_7)
EUI9T=t(EUI_9)
EUI11T=t(EUI_11)
EUI13T=t(EUI_13)
EUI15T=t(EUI_15)
EUI17T=t(EUI_17)
EUI19T=t(EUI_19)

#set up EUI error data frame
EUI_Error=data.frame()
EUI_Error[1:9,1]=c(3,5,7,9,11,13,15,17,19)
#add 3-building sample EUI_Error
EUI_Error[1,2]=colMeans(EUI3T)[4]
EUI_Error[1,3]=colMeans(EUI3T)[5]
#add 5-building sample EUI_Error
EUI_Error[2,2]=colMeans(EUI5T)[4]
EUI_Error[2,3]=colMeans(EUI5T)[5]
#add 7-building sample EUI_Error
EUI_Error[3,2]=colMeans(EUI7T)[4]
EUI_Error[3,3]=colMeans(EUI7T)[5]
#add 9-building sample EUI_Error
EUI_Error[4,2]=colMeans(EUI9T)[4]
EUI_Error[4,3]=colMeans(EUI9T)[5]
#add 11-building sample EUI_Error
EUI_Error[5,2]=colMeans(EUI11T)[4]
EUI_Error[5,3]=colMeans(EUI11T)[5]
#add 13-building sample EUI_Error
EUI_Error[6,2]=colMeans(EUI13T)[4]
EUI_Error[6,3]=colMeans(EUI13T)[5]
#add 15-building sample EUI_Error
EUI_Error[7,2]=colMeans(EUI15T)[4]
EUI_Error[7,3]=colMeans(EUI15T)[5]
#add 17-building sample EUI_Error
EUI_Error[8,2]=colMeans(EUI17T)[4]
EUI_Error[8,3]=colMeans(EUI17T)[5]
#add 19-building sample EUI_Error
EUI_Error[9,2]=colMeans(EUI19T)[4]
EUI_Error[9,3]=colMeans(EUI19T)[5]
colNames(EUI_Error) <- c("sampleSize","wireframe_Error", "Reference_Error")
EUI_Error

#transpose Energy totals to permit column summing
Energy3T=t(Energy_3)
Energy5T=t(Energy_5)
Energy7T=t(Energy_7)
Energy9T=t(Energy_9)
Energy11T=t(Energy_11)
Energy13T=t(Energy_13)
Energy15T=t(Energy_15)
Energy17T=t(Energy_17)
Energy19T=t(Energy_19)

#set up Energy error data frame
Energy_Error=data.frame()
Energy_Error[1:9,1]=c(3,5,7,9,11,13,15,17,19)
#add 3-building sample Energy_Error
Energy_Error[1,2]=colMeans(Energy3T)[4]
Energy_Error[1,3]=colMeans(Energy3T)[5]
#add 5-building sample Energy_Error
Energy_Error[2,2]=colMeans(Energy5T)[4]
Energy_Error[2,3]=colMeans(Energy5T)[5]
#add 7-building sample Energy_Error
Energy_Error[3,2]=colMeans(Energy7T)[4]
Energy_Error[3,3]=colMeans(Energy7T)[5]
#add 9-building sample Energy_Error
Energy_Error[4,2]=colMeans(Energy9T)[4]
Energy_Error[4,3]=colMeans(Energy9T)[5]
#add 11-building sample Energy_Error
Energy_Error[5,2]=colMeans(Energy11T)[4]
Energy_Error[5,3]=colMeans(Energy11T)[5]
#add 13-building sample Energy_Error
Energy_Error[6,2]=colMeans(Energy13T)[4]
Energy_Error[6,3]=colMeans(Energy13T)[5]
#add 15-building sample Energy_Error
Energy_Error[7,2]=colMeans(Energy15T)[4]
Energy_Error[7,3]=colMeans(Energy15T)[5]
#add 17-building sample Energy_Error
Energy_Error[8,2]=colMeans(Energy17T)[4]
Energy_Error[8,3]=colMeans(Energy17T)[5]
#add 19-building sample Energy_Error
Energy_Error[9,2]=colMeans(Energy19T)[4]
Energy_Error[9,3]=colMeans(Energy19T)[5]
colNames(Energy_Error) <- c("sampleSize","wireframe_Error", "Reference_Error")
Energy_Error

```