Uncertainty in Building Energy Simulation and Its Implications for the British Columbia Energy Step Code

Sepehr Foroushani
Planning & Development, City of Richmond, BC, Canada

Abstract

As performance-based building energy codes proliferate, building energy simulation (BES) becomes an essential tool to verify and document code compliance. Accordingly, uncertainty in BES results becomes increasingly important to various stakeholders, including local governments. The British Columbia Energy Step Code (ESC) is one of the latest performance-based codes in North America. The December 2019 revision to the Code has introduced relative thermal performance targets for the building envelope which are measured in comparison to a "reference" building. In this paper the uncertainty of typical building energy simulations using the HOT2000 simulation tool is studied. Using computational experiments based on two scenarios for the uncertainty of model inputs, it is shown that the relative thermal performance metric of ESC can have uncertainties larger than some of the relative performance targets of the Code, prohibiting reliable assessment of compliance.

Introduction

Imagine a civic regulation that limits buildings to 10 m in height. Even if not explicitly mentioned, it is understood that this threshold has some tolerance; it is common sense that the height of a building cannot be measured within 1 mm or even 1 cm. Therefore, a building reported as 10.001 m or even 10.01 m in height would not reasonably be deemed in violation of the regulation.

Due to the difficulty of measuring the height of a building that does not yet exist, the regulation allows, or rather requires, the use of "building height models" to show compliance at the time of application for a building permit. Like any physical model, these would be mathematical relations that allow the determination of a certain physical parameter, in this case the building height, based on the knowledge of other physical (or physically determined) parameters. The model outputs inherently contain uncertainty due to not only the systematic errors of the model, but also uncertainty in the model inputs.

Consider one such model which estimates the height of a building based on the number of its building blocks, e.g. bricks, and the thickness of each block. Aside from systematic errors, e.g. due to neglecting the mortar joints between the bricks, the model has input uncertainty, e.g. due to uncertainty in the thickness of the bricks.

Suppose that using the model, the height of a certain design is estimated at 9.98 m. Moreover, the uncertainty of this modeling result is estimated at ±0.01 m. It is reasonable to consider the design compliant with the regulation since the "worst-case" estimate of the building height is 9.99 m, still below the threshold (10 m).

Now, to promote further formal harmony in neighborhoods, a second clause of our hypothetical regulation also stipulates that any new building must also be at least 0.25% shorter than the neighboring buildings. For instance, if the design mentioned earlier is adjacent to a house that is 10 m high, its height must not exceed 9.975 m. While the height modeling result introduced earlier (9.98 m) may suggest the proposed design is non-compliant, it must be recalled that the modeling result is not 9.98 m; it is 9.98±0.01 m. Given the magnitude of uncertainty in the modeling result, compliance (or non-compliance) cannot be conclusively established. Either models with lower uncertainty must be utilized, or, if a desire exists to use the "building-block" model, the relative height allowance must be accordingly revised to allow meaningful comparisons.

This paper is an attempt to show that some of the relative performance targets of the British Columbia *Energy Step Code*, measured in comparison to a "Reference House", are essentially like the 0.25% relative height threshold in the example above: given the typical uncertainties of the dominant modeling tool, compliance with those performance targets cannot be meaningfully evaluated.

A high-level discussion of uncertainty in building energy simulation is presented, followed by a succinct overview of the Energy Step Code and its relative performance criteria. A simple uncertainty analysis is then presented to establish typical uncertainties associated with HOT2000 (Natural Resources Canada) building energy simulations that are almost universally used to demonstrate compliance of houses with the British Columbia Energy Step Code. A design based on building permit applications submitted to the City of Richmond is used in the study. This study is limited to input uncertainties; it does not concern systematic modeling errors. It is also limited in scope to small residential buildings, referred to as "Part 9" buildings in the Building Code terminology.

Uncertainty in Building Energy Simulation

Uncertainty has long been recognized as an inherent and inseparable feature of the human knowledge. In fact, uncertainty is *part* of our knowledge. Despite our long recognition of uncertainty and its importance, specifically in experimental measurements of physical quantities, quantifying and reporting uncertainty have only recently become standard practice, and even more recently a requirement, in scientific studies. In computational methods, the study and documentation of uncertainty are still not as developed or widespread as in experimental studies.

As pointed out by de Wit (2004), the predominant lack of concern for uncertainty in building energy simulation is surprising: "if we consider building simulation as an instrument, which aims to contribute to decision-makers' understanding and overview of the decision-problem, it seems natural that uncertainties [be] assessed and communicated" (de Wit, 2004).

With the proliferation of building energy simulation for design, analysis and diagnosis, the importance of uncertainty in building energy models increases. In addition, as performance-based building energy codes and standards emerge, building energy simulation becomes an essential tool to verify and document code compliance. Accordingly, the study and quantification of uncertainties associated with building energy simulation, and their implications in the comparison of predicted and required performance targets, become increasingly important to the designers, builders and regulators.

Uncertainty in the modeled energy performance of a building can be divided into two main categories. The first category is modeling uncertainty which has to do with the systematic error associated with the models used to describe and simulate various physical phenomena, e.g. long-wave radiation between surfaces. Numerical errors occurring during numerical solution of governing equations can also be included in this category. The second category is input uncertainty which arises from uncertain or underdetermined knowledge of the building components (dimensions, thermo physical properties, etc.) and systems (operating conditions, efficiency etc.) as well as external factors such as weather data (temperature, humidity, wind speed and direction etc.). Examples of uncertainty analysis of building performance simulation include the work of Macdonald (2002), de Wit (2004), Hopfe et al. (2007), and Hopfe & Hensen (2011).

It is noteworthy that the choice of model influences the contribution of input uncertainties. Because sophisticated models generally entail more parameters and inputs, they lead to larger input uncertainties. Given a certain simulation tool, i.e. set of models and solution methodology, it is the input uncertainties that must be examined, quantified and documented.

British Columbia Energy Step Code

The British Columbia Energy Step Code (ESC) is an optional compliance path in the British Columbia Building Code to incentivize or require increased energy efficiency in new construction (Building and Safety Standards Branch, 2017). The ESC has been designed as a transition plan to achieve net-zero energy ready buildings by 2032.

In addition to more stringent energy efficiency requirements, ESC also entails a fundamental shift from prescriptive to performance requirements. Whereas in the prescriptive approach, various building components (e.g. insulation, windows) and systems (e.g. furnaces, water heaters, lighting) must meet specific requirements, the performance-based approach focuses on functions of the building as a whole, without dictating specifications for individual components and systems. Many building energy efficiency certification programs such as Natural Resources Canada's *Energy Star for New Homes* and the Passive House Standard are performance-based.

ESC is based on performance targets for the airtightness of the building, the thermal performance of the building envelope, and the efficiency of the building systems. For small residential buildings less than 600 m^2 in floor area and less than four storeys in height, the ESC sets out limits for the air leakage rate as well as *thermal energy demand intensity* (TEDI), which characterizes thermal performance of the envelope, and *mechanical energy use intensity* (MEUI), which characterizes the energy use of mechanical systems. See Equations (1) and (2).

$$\mathrm{TEDI} = \frac{Q_{\mathrm{aux}}}{A} \qquad \left[\frac{\mathrm{kWh}}{\mathrm{m^2 a}}\right] \tag{1}$$

$$\mathrm{MEUI} = \frac{E_{\mathrm{tot}} - E_{\mathrm{plug}}}{A} \qquad \left[\frac{\mathrm{kWh}}{\mathrm{m^2 a}}\right] \tag{2}$$

In these equations, Q_{aux} is the annual auxiliary heating demand, which is the total space heat loss offset by the usable internal and solar heat gains; A is the heated area of the house; E_{tot} is the total annual energy use of the building; and E_{plug} is the annual plug (base) load.

The air leakage rate is determined based on blower-door tests, while MEUI and TEDI are calculated based on building energy simulations.

Each "Step" is a set of performance targets (thresholds) for air leakage, TEDI, and MEUI, particular to the building archetype and the climate zone. For example, achieving Step 2 in Climate Zone 4 for a house with more than 210 m^2 heated area, requires an air leakage rate no more than 3.0 ACH_{50}, TEDI $\leq$ 35 kWh/m^2/a and MEUI $\leq$ 65 kWh/m^2/a.

The Relative Performance Targets

In addition to absolute performance targets, the British Columbia Energy Step Code contains alternative performance targets that are measured relative to a "reference" building, a house of identical shape and size, built to the minimum prescriptive requirements of the Building Code. The British Columbia Building Code 2018 (Building and Safety Standards Branch, 2018) contained relative performance targets for building systems, based on the EnerGuide rating (Natural Resources Canada, 2019) of the house, as an alternative to the absolute MEUI targets. For instance, a house with more than 210 m^2 of conditioned space in Climate Zone 4 can achieve Step 2 with an EnerGuide rating of at least 10% better than the Reference House, instead of MEUI ≤ 65 $kWh/m^2/a$. The December 2019 revision to the Code (Building and Safety Standards Branch, 2019) introduced relative performance targets for the thermal performance of the envelope, as an alternative compliance pathway to the absolute TEDI targets. For instance, a house in Climate Zone 4 can achieve Step 2 with a thermal performance at least 5% better than the Reference House, instead of TEDI ≤ 35 $kWh/m^2/a$. Note that at the time of the preparation of this manuscript, the detailed calculation methodology for the "better thermal performance" metric was still under development by the Province of British Columbia. See Table 1.

Table 1: Performance targets of the Energy Step Code (2019) for small residential buildings in Climate Zone 4 with more than 210 m^2 of conditioned space of which more than 50% is served by space cooling equipment

Step	Air Leakage Rate [ACH_{50}]	Building Systems		Building Envelope	
		MEUI [$kWh/m^2/a$]	Better ERS* [%]	TEDI [$kWh/m^2/a$]	Better Thermal* [%]
1	N/A	N/A	0	N/A	0
2	3.0	65	10	35	5
3	2.5	55	20	30	10
4	1.5	45	40	20	20
5	1.0	30	N/A	15	50

* Compared to the Reference House

Relative performance targets compared to the reference building have serious shortcomings, as documented in a recent report (City of Richmond, 2020) and increasingly understood by various stakeholders. Setting aside the fundamental, methodological problems of that approach, the present paper focuses on the specific targets introduced to ESC and their relation with the uncertainty of typical building energy simulations performed to assess compliance.

Methodology

To assess the uncertainty of ESC metrics evaluated based on HOT2000 simulations, particularly the absolute and relative thermal performance metrics, a "model house" was chosen based on an actual single-family house built in Richmond, British Columbia (Climate Zone 4; ~2800 Heating Degree Days) in 2019 to meet Step 1. In Figure 1, the modeled energy performance of the model house is compared with the average of those 133 houses. The energy consumption is reported by end-use and as percentage of the rated energy consumption which is the total energy consumption of the house minus the plug (base) loads. Heat loss from various envelope assemblies and due to infiltration as well as the auxiliary energy required for space heating are reported as percentage of the total annual heat loss from the house. The Energy Step Code metrics of the model house are also a good representative of the sample, within half standard deviation of the mean. See Table 2. The model house therefore deemed a good representative of the first 133 single-family houses built under the ESC in Richmond.

Table 2: Energy Step Code performance metrics of the model house vs. 133 houses in Richmond

	Air Leakage Rate [ACH_{50}]	MEUI [$kWh/m^2/a$]	TEDI [$kWh/m^2/a$]
Model house	3.2	80	57
Mean | standard deviation (N=133)	3.1 | 1.0	75 | 13	53 | 11

Given that the HOT2000 simulation engine is based on the Bin Method, the gross annual space hear loss, Q_{loss}, can be written as:

$$Q_{\text{loss}} = \sum_i N_i \left[\sum_j U_j A_j + \rho C_p \dot{V} \right] \left(T - T_{\text{o},i} \right)^+ \quad (3)$$

where N_i denotes the number of hours when the indoor temperature T exceeds the outdoor bin temperature $T_{\text{o},i}$; U_j and A_j are respectively the total transmission coefficient and surface areas of the envelope component j; ρ and C_p are respectively the density and specific heat of air; and $\dot{V}$ is the volumetric rate of air infiltration into the house. See ASHRAE (2017) for more details on the Bin Method.

The auxiliary energy demand can then be calculated as:

$$Q_{\text{aux}} = Q_{\text{loss}} - Q_{\text{solar}} - Q_{\text{internal}} \quad (4)$$

where Q_{solar} and Q_{internal} denote the usable solar and internal heat gains, respectively. In HOT2000, Q_{solar} and Q_{internal} are determined based on solar angle calculations and occupancy and appliance operation schedules, respectively.

Finally, the total energy consumption of the building can then be written as:

$$E_{\text{tot}} = E_{\text{SH}} + E_{\text{DHW}} + E_{\text{vent}} + E_{\text{SC}} + E_{\text{plug}} \quad (5)$$

The terms on the right-hand side of Equation 5 denote respectively the energy demand for space heating, domestic hot water heating, ventilation, space cooling and plug loads. Note that:

$$E_{\text{SH}} = \frac{Q_{\text{aux}}}{\eta_{\text{SH}}} \quad (6)$$

where η_{SH} denotes the efficiency of the space heating system.

Given Equations 1, 3 and 4, and ignoring the uncertainty in weather data ($T_{\text{o},i}$, N_i) and properties of air (ρ,C_{p}), the uncertainty in TEDI is mainly dictated by the uncertainty in U_j, A_j and $\dot{V}$.

The independent inputs studied here to determine the uncertainty in U_j, A_j and $\dot{V}$ are the building dimensions, specific thermal resistivity of insulation material, thermal/solar specifications of fenestration (U-value, SHGC), measured volumetric rate of air leakage, and efficiency of mechanical equipment. Two uncertainty scenarios were considered, as shown in Table 3.

In the low-uncertainty scenario, uncertainty in the specific thermal resistivity of insulation materials and U-value of windows was picked based on typical uncertainty of calorimetric measurements using guarded heated plates. See for instance the paper by Bomberg & Solvason (1981). The uncertainty in SHGC was determined based on the work of Wright (1995). In the high-uncertainty scenario, an uncertainty of 10% was assumed for R-values, U-values and the SHGC to account for product variability ("batch uncertainty") and repeatability of characterization tests. Uncertainty in the rate of air leakage was chosen based on the nominal error of flow meters commonly used in blower-door test measurements of air leakage, e.g. Retrotec (2017).

Table 3: Independent model parameters and associated uncertainties

Independent parameter	Uncertainty	
	High	**Low**
Building dimensions	± 0.02 m	± 0.01 m
Thickness of insulation layer	± 0.002 m	± 0.001 m
Specific thermal resistivity of insulation	± 10%	± 2%
U-value of windows	± 10%	± 2%
SHGC of windows	± 10%	0.02
Volumetric rate of air leakage	± 2%	
Efficiency of mechanical equipment	± 2%	

Uncertainty in the HOT2000 input parameters was then calculated based on simple propagation of the uncertainties of the independent parameters. See Table 4. For simplicity, the variation in the surface area of the envelope assemblies (windows, walls, roofs, floors) was ignored; uncertainty in the building dimensions was only propagated to the heated floor area and the building volume. In calculating the uncertainty of the effective R-value of the opaque envelope assemblies, only the uncertainty in the R-value of the insulation layer (due to uncertainty in the layer's specific resistivity and thickness) was considered. Due to the small contribution of heat loss from doors to the total heat loss, inputs associated with doors were not considered.

For each uncertainty scenario, twelve computational experiments were carried out where each of the input parameters listed in Table 4 was changed to a random value within its range (nominal value ± uncertainty). Note that the number of experiments (12) is more than 4/3 times the number of independent parameters (7), as recommended by Morris (1991).

The ESC metrics were then calculated according to Equations 1 and 2. As mentioned earlier, the calculation methodology for the relative thermal performance metric was not finalized at the time of the preparation of this paper. Instead, the percentage difference between the TEDI's of the Proposed and Reference houses was calculated.

Table 4: Uncertainty in HOT2000 inputs

Model input	Nominal value	Uncertainty	
		High	**Low**
Building heated area [m^2]	310.0	± 0.70	± 0.35
Building volume [m^3]	1027.9	± 8.54	± 4.27
Effective R-value of opaque assemblies [m^{2}K/W]			
Exposed roof	6.85	± 0.07	± 0.03
Main ceiling	6.94		
Garage wall	2.97		
Main floor I	2.76		
Main floor II	2.29		
Upper floor wall I	3.93		
Upper floor wall II	3.20		
Exposed floors	4.90		
Foundation	2.10	± 0.02	± 0.00
Window U-value [W/m^2/K]	1.48	± 0.15	± 0.03
Window SHGC [-]	0.29	± 0.03	± 0.02
Air leakage rate [ACH_{50}]	3.17	± 0.08	± 0.07
Boiler efficiency [%]	95%	± 2%	
HRV effectiveness @ 0°C [%]	70%	± 2%	
HRV effectiveness @ -25°C [%]	60%	± 2%	

Results

Table 5 shows the ESC metrics for the computational experiments as well as the base case (nominal inputs) and the Reference House. The first 12 tests correspond to the high-uncertainty scenario. Tests 13-24 are based on the low-uncertainty scenario.

According to the results shown in Table 5, the 95% confidence uncertainty (2σ) of TEDI calculations is 3.0 $kWh/m^2/a$ for the high-uncertainty scenario and 1.2 $kWh/m^2/a$ for the low-uncertainty scenario. Assuming the same level of uncertainty for the Reference House, these results suggest that the difference between the TEDI's of the Proposed and Reference houses can be known within 4.2 $kWh/m^2/a$ in the high-uncertainty scenario, and within 1.7 $kWh/m^2/a$ in the low-uncertainty scenario. In relative terms, these uncertainty levels correspond to 6.9% and 2.8% of the Reference House TEDI (61 $kWh/m^2/a$). Note that the 95% confidence uncertainty in the other relative performance criterion, namely the % better EnerGuide rating, is much lower: 2.6% in the high-uncertainty scenario and 1.0% in the low-uncertainty scenario.

It should be noted that the Reference House, and accordingly its TEDI, changes with the house design. Therefore, although the absolute uncertainty levels calculated here may be taken as typical of building energy simulation results for typical houses in Richmond, the relative uncertainty will differ from case to case. See Figure 2 where the distribution of the Reference House TEDI based on 125 cases in Richmond is shown. Note the wide range of Reference House TEDI's, 35-75 $kWh/m^2/a$. Depending on the uncertainty scenario and the Reference House, uncertainty in the TEDI differential can be as low as 2.3% ($TEDI_{Ref} \geq 75$ $kWh/m^2/a$) or as high as 12.0% ($TEDI_{Ref} \leq 35$ $kWh/m^2/a$). For the average Reference House (TEDI=57 $kWh/m^2/a$), the uncertainty scenarios studied here can lead to 3.0% to 7.4% uncertainty in the TEDI differential.

Conclusion

A simple uncertainty analysis was performed to assess the typical input uncertainties of building energy simulations performed using HOT2000. Computational experiments were conducted on a model house chosen to represent a sample of more than 100 houses in Richmond, British Columbia. The parameters characterizing the thermal performance of the building envelope, infiltration rate into the building, and the efficiency of mechanical equipment were randomly changed within their 95% confidence range. Two scenarios representing high and low levels of uncertainty were considered. Results show that the relative uncertainty of the TEDI differential can be as high as the relative performance target of Step 3 (10%). On average, typical TEDI differential calculations based on HOT2000 simulations may have uncertainties equivalent to the relative performance target of Step 2 (5%).

Given the observed levels of uncertainty, the relative thermal performance targets of Step 2 and 3 of the Energy Step Code seem too low to be meaningfully established based on HOT2000 simulations. These results are even more concerning given the latest proposed changes to the National Building Code of Canada and the National Energy Code of Canada for Buildings (Natural Resources Canada, 2020) which introduce similar relative targets. It is recommended that the relative performance targets in the Codes be revised with attention to uncertainties that are inherent to building energy simulation, regardless of the building energy modelling approach or simulation tool.

Finally, it is noteworthy that the general approach taken in this paper can also be utilized to establish acceptable levels of parameter uncertainty for building energy simulations: sensitivity analyses must be performed to determine maximum input uncertainties that lead to a desired level of uncertainty in the performance metrics.

Nomenclature

ACH_{50}	Air change per hour (at 50 Pa pressure difference)
ERS	EnerGuide Rating System
ESC	Energy Step Code
HRV	Heat recovery ventilator
MEUI	Mechanical Energy Use Intensity [$kWh/m^2/a$]
REC	Rated energy consumption [kWh/a]
Ref	EnerGuide Reference House
SHGC	Solar heat gain coefficient [-]
TEDI	Thermal Energy Demand Intensity [$kWh/m^2/a$]
A	Surface area [m^2]
C_p	Constant-pressure specific heat [kJ/kg/K]
E	Annual energy use [kWh/a]
N	Number of hours
Q	Annual thermal energy demand [kWh/a]
T	Temperature [°C]
U	Transmission coefficient [$W/m^2/K$]
$\dot{V}$	Volumetric infiltration rate [L/s]
ρ	Density [kg/m^3]
σ	Standard deviation

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Table 5: Results of computational experiments — Energy Step Code metrics
(Tests 1-12: High-uncertainty scenario; Tests 13-24: Low-uncertainty scenario)

Case	Heated Area [m^2]	Air Leakage Rate [ACH_{50}]	REC [GJ/a]	Better ERS* [%]	MEUI [$kWh/m^2/a$]	TEDI [$kWh/m^2/a$]
Reference House	310.0	2.50	104	—	93	61
Base case	310.0	3.17	92	9	83	58
Test 1	310.4	3.24	91	9	82	57
Test 2	309.6	3.24	91	10	81	56
Test 3	310.2	3.19	94	7	85	58
Test 4	310.2	3.19	91	10	81	55
Test 5	310.0	3.22	95	7	85	58
Test 6	309.5	3.16	91	10	82	56
Test 7	309.8	3.22	95	7	85	58
Test 8	309.7	3.17	92	9	83	57
Test 9	309.4	3.19	95	7	85	60
Test 10	310.2	3.23	89	11	80	54
Test 11	309.6	3.21	93	8	83	58
Test 12	310.5	3.19	92	9	83	57
Mean	309.9	3.2	92	8.6	83	57
Std. Dev.	0.35	0.03	1.8	1.3	1.6	1.5
Test 13	310.3	3.20	92	9	85	59
Test 14	310.2	3.18	95	7	84	58
Test 15	310.1	3.11	94	8	84	58
Test 16	309.9	3.16	94	7	83	58
Test 17	309.8	3.19	92	9	83	57
Test 18	310.2	3.11	93	8	83	58
Test 19	309.9	3.11	93	8	84	58
Test 20	310.2	3.17	93	8	83	57
Test 21	310.1	3.23	93	8	84	59
Test 22	310.3	3.18	94	7	85	58
Test 23	309.7	3.10	94	7	84	58
Test 24	310.0	3.10	94	8	84	58
Mean	310.0	3.2	94	7.8	84	58
Std. Dev.	0.20	0.04	0.7	0.5	0.7	0.6

* Compared to the Reference House

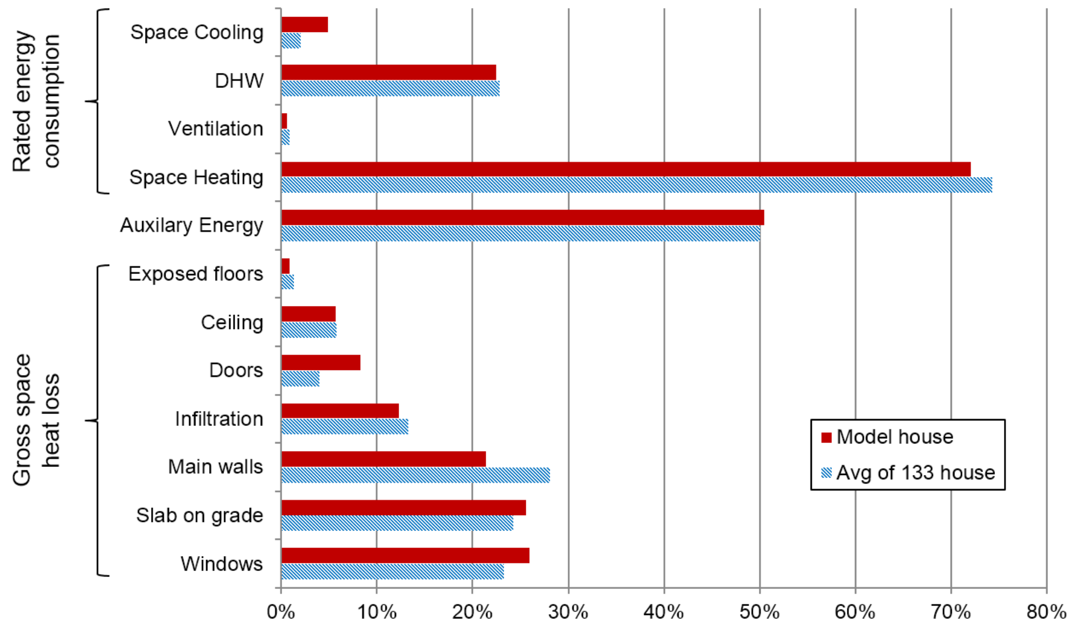

Figure 1: Energy consumption and heat loss profiles of the model house used in this study and average of 133 "Step 1" houses in Richmond, British Columbia

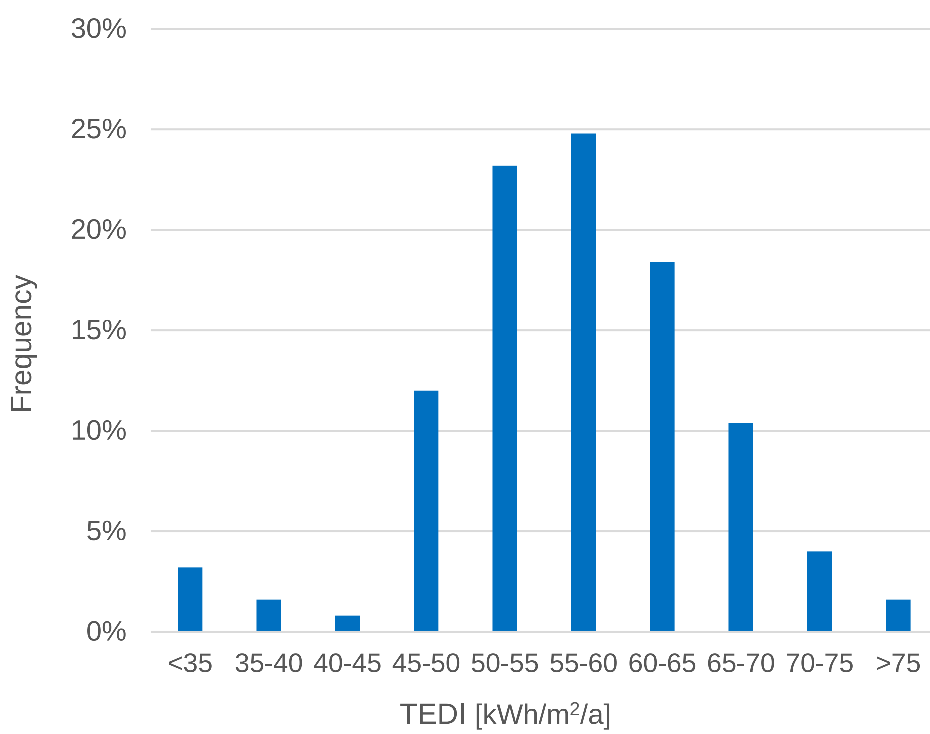

Figure 2: Distribution of the Reference House TEDI based on 125 cases in Richmond (Mean: 57 kWh/m^2/a, Standard deviation: 9 kWh/m^2/a)