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Evaluating thermal performance of vertical building envelopes: Case studies in a Canadian university campus

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ABSTRACT

Campus buildings at the University of Victoria (UVic) were largely constructed before the advent of building energy codes. The University is in the process of commissioning vertical building envelope upgrades/retrofits with added intention of addressing potential energy and greenhouse gas (GHG) savings in their building stock. The aim of this paper is to present the methodology adopted to evaluate potential energy savings from vertical envelope retrofits of 49 non-residential buildings across the campus portfolio, and to further validate those savings through more detailed energy models for a subset of buildings. To this end, the thermal performance of a building envelope was quantified based on its heat loss coefficient (UA), obtained from multiplying its surface area (A) by its thermal transmittance (U-value). Heat loss (UA) calculations were used as an energy loss metric to inform envelope rehabilitation prioritization, in addition to data gathered from building envelope condition assessments (BECAs). UA data were also analyzed against other building data such as floor area, vertical envelope area, vertical area to floor area ratio (VFAR), window-wall ratio (WWR), age, and type of construction for potential correlations. Finally, archetype energy models were used to evaluate the impacts of envelope retrofits on energy and GHG savings on three selected buildings. The outcomes of this study allow the University to weigh the benefits of improved energy performance from envelope retrofits against associated capital cost expenditures.

1. Introduction

Energy consumption in the built environment has increased considerably over the past decades mainly as a result of population growth, occupants spending more time indoors, higher expectations of indoor comfort (thermal and air quality), and a changing climate. According to the International Energy Agency (IEA), building operation and construction collectively consume over one-third of total global energy, and are responsible for almost 40% of direct and indirect greenhouse gas (GHG) emissions [1]. Most building energy codes and regulations focus on improving energy efficiency of new buildings. However, energy consumption of existing buildings is an area which deserves more attention by energy policymakers since existing buildings often have higher energy use intensities (EUIs) than new construction; further, the vast majority of building stock in any given period are existing and are in need of some form of rehabilitation or retro-commissioning due to deteriorating building envelopes and/or mechanical and electrical systems, presenting an economic opportunity to reduce their energy consumption [2]. To this end, various energy assessment methods have been developed to enhance the energy performance of existing buildings [3–9].

Studies analyzing existing building energy performance have typically focused on commercial and residential buildings, while studies focused on educational (university/school) buildings are limited despite their relatively high energy consumption, large size, and different occupancy schedules. Some university campuses contain a substantial number of buildings within their portfolio, collectively accounting for significant GHG emissions. For instance, in the UK, GHG emissions generated by universities increased from 1.78 to 2.05 tCO_2e between 1990 and 2005. In China, 40% of the public sector's energy is consumed by universities, representing the largest sector of public building GHG emissions [10]. Similarly, universities and colleges in the US spend

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almost USD $6 billion annually on energy; a substantial 25% of this cost could be saved by improving the energy performance of this sector, according to the U.S. Department of Energy (DOE) [11]. In Canada, educational buildings contribute almost 16% of total greenhouse gas (GHG) emissions among 11 sectors. Higher education institutions such as universities and colleges account for almost 60% of the total energy consumed by the educational sector [12]. Given their sizeable share of building energy consumption, addressing energy efficiency of educational buildings presents a considerable opportunity to curb GHG emissions.

Among retrofit strategies, upgrading the building envelope plays a key role in improving existing building energy performance. Previous studies have introduced different methodologies for prioritizing buildings in a portfolio for energy retrofits [13–16], however; using particular criteria as a methodology to evaluate and rank buildings for envelope retofits is missing in literature. In practice, building envelopes undergo retrofits when its physical condition dictates. However, physical condition of a building envelope should not be used as the only metric for determining a retrofit priority in a portfolio since it does not necessarily correlate with its thermal performance. Another criterion sometimes used by portfolio managers for ranking buildings is energy use intensity (EUI). However, this metric can be a misleading indicator for opportunities to improve building envelope performance, since EUI apart from building envelope, depends on other variables such as internal loads, building typology, schedules, and efficiency and controls of mechanical systems. Furthermore, EUI data is not always available for existing buildings due to lack of metering, which would prevent even the most basic energy consumption benchmarking. Consequently, building envelope thermal performance should be evaluated independently for more accurate prioritization.

Current quantitative methods for thermal assessments of building envelopes are based on simplified assumptions from historical codes and references [17–20]. This approach does not reflect actual performance due to temporal degradation of components, and ignores the increased heat losses from thermal bridges. For instance, disregarding thermal bridges can result in a 20%–70% underestimation of the total heat flow through walls [21]. In recent years, modern computer simulation tools have enabled a better estimation of thermal bridging effects. However, a large-scale simulation-based thermal assessment of building envelopes requires access to component details in architectural drawings and is time-consuming. Therefore, large-scale assessments of this nature require balancing accuracy of results with work efficiency (time & cost). It should also be noted that architectural design parameters such as building geometry, window to wall ratio (WWR), and structural framing type can affect building envelope thermal performance. Collectively, these aspects form the motivation to develop an approach for evaluating and ranking building envelope thermal performance.

Effectiveness of retrofit strategies should be evaluated in terms of energy and cost savings by considering regional climate differences. Previous campus-level investigations mainly focused on energy savings of buildings in Europe, where retrofits are more economically justifiable due to high energy costs [22–29]. However, very few studies investigated the energy and cost savings associated with retrofits in Canadian school/university buildings, where climate, construction practices, building codes, utility costs, carbon emission factors, and carbon taxes are different [30–32]. In Canada, building codes are evolving to meet multiple objectives, including reducing energy consumption and greenhouse gas emissions, increasing resiliency and passive survivability. For example, the City of Toronto, City of Vancouver and the Province of British Columbia have included the Thermal Energy Demand Intensity (TEDI) metric in addition to Energy Use Intensity (EUI) into policy document in an effort to address the performance of the building envelope and ventilation air heating requirements in new construction. While EUI target is typically attainable by mechanical or lighting system upgrades, TEDI elevates the importance of the building envelope, which is viewed as one of the most robust energy saving measures in a building. Notably, no Canadian jurisdictions have adopted energy performance requirements for existing buildings. Hence, an absence of building codes for existing buildings along with differences in climate and energy costs from those in Europe prompted the researchers of this study to contribute some insights into literature, which could be informative for Canadian universities to reduce GHG emissions within their portfolio as the Canadian government targets an 80% GHG emissions reduction in its operations by 2050, relative to 2005 [33].

This paper presents a study conducted at the University of Victoria (UVic) campus in British Columbia, Canada. The university has initiated a comprehensive building investigation process to prioritize and plan envelope rehabilitation work across their portfolio, intending to incorporate potential energy and GHG savings into their decision-making criteria. Recent building envelope condition assessments (BECAs) identified that vertical building envelopes on many buildings on campus were in poor condition and would likely require rehabilitation in 5–10 years, while roofs were generally in good condition.

Hence, the proposed study aimed to demonstrate a practical approach to rapidly assess vertical building envelope thermal performance of 49 non-residential buildings across the university campus. This methodology yields metrics that serve as a complementary decision-making criteria to BECAs that routinely carried out by building envelope engineers/professionals. In addition, whole-building energy simulations were conducted using EnergyPlus v8.8 to evaluate the impacts of envelope retrofits on energy efficiency, cost and GHG savings.

2. Methodology

2.1. Overview and data collection

In this study, vertical building envelope thermal performance quantified by performing heat loss (UA) calculations, obtained by multiplying the surface area (A) of building envelope by its thermal transmittance (U-value), while also taking into account heat losses through linear thermal bridges. This process of evaluation was found to be faster than individual whole-building simulations or energy audits. Critical analyses were performed to assess the impact of architectural parameters such as floor area, vertical envelope area, vertical envelope area to floor area ratio (VFAR), window wall ratio (WWR), age, and type of construction on (UA) calculations. The VFAR metric is similar to a building's surface areas to volume ratio, (compactness); however, VFAR may be considered a more informative shape metric since walls and windows have significantly higher U-values than roofs and floors. Since this study focuses on the evaluation of vertical building envelopes, this metric was considered more appropriate for comparative analysis.

Subsequent to the UA analysis, whole-building energy models of three selected buildings were developed by EnergyPlus 8.8 energy simulation software [34]. Two of the buildings were selected based on the highest envelope energy losses as indicated by UA calculations, while the third was based on a poor overall condition of its building envelope (per the BECA). The purpose of energy modeling was to investigate economics of available energy savings from implementing envelope energy conservation measures (ECMs). The energy model for the smaller building was developed based on actual space layouts, while archetype (approximate) models were developed for the other two larger and more complex buildings. The value of archetype models is realized in cases where other buildings are very similar in shape, internal loads, and operations, such that it could be possible to apply conclusions from one building to other similar buildings. Archetype modeling methodology is explained further in Section 3.2.

Input data required for UA calculations were collected from technical documents such as building drawings, literature sources such as ASHRAE Handbook of Fundamentals [35], the Building Envelope Thermal Bridging Guide (BETBG) [21], and a simple on-site audit of fenestration. For building energy simulations, input data were obtained from a variety of sources:

- Measured electricity and natural gas consumption data for each building provided by the university
- National Energy Code of Canada for Buildings (NECB 2015) [36].
- ASHRAE Standard for Ventilation for Acceptable Indoor Air Quality (ASHRAE 62.1-2010) [37].
- Original (as-built) architectural and mechanical drawings
- Thermal transmittance of building envelope (U-values) obtained from preliminary UA calculations

The analysis framework conducted on the case studies is illustrated in Fig. 1.

2.2. Case studies

Fig. 2 shows the layout of buildings on campus. The 49 non-residential buildings studied are categorized into four groups according to high, moderate, low or minimal potential risks of building envelope failure (see Fig. 2). The category assigned to each building is determined according to its BECA 'score'. The results of the condition assessment formed one criterion for building prioritization.

The names of buildings studied are provided in Appendix A1, and mainly consisted of classrooms, laboratory and administrative offices. Heating systems are electric, gas, or district hot-water (hydronic) based.

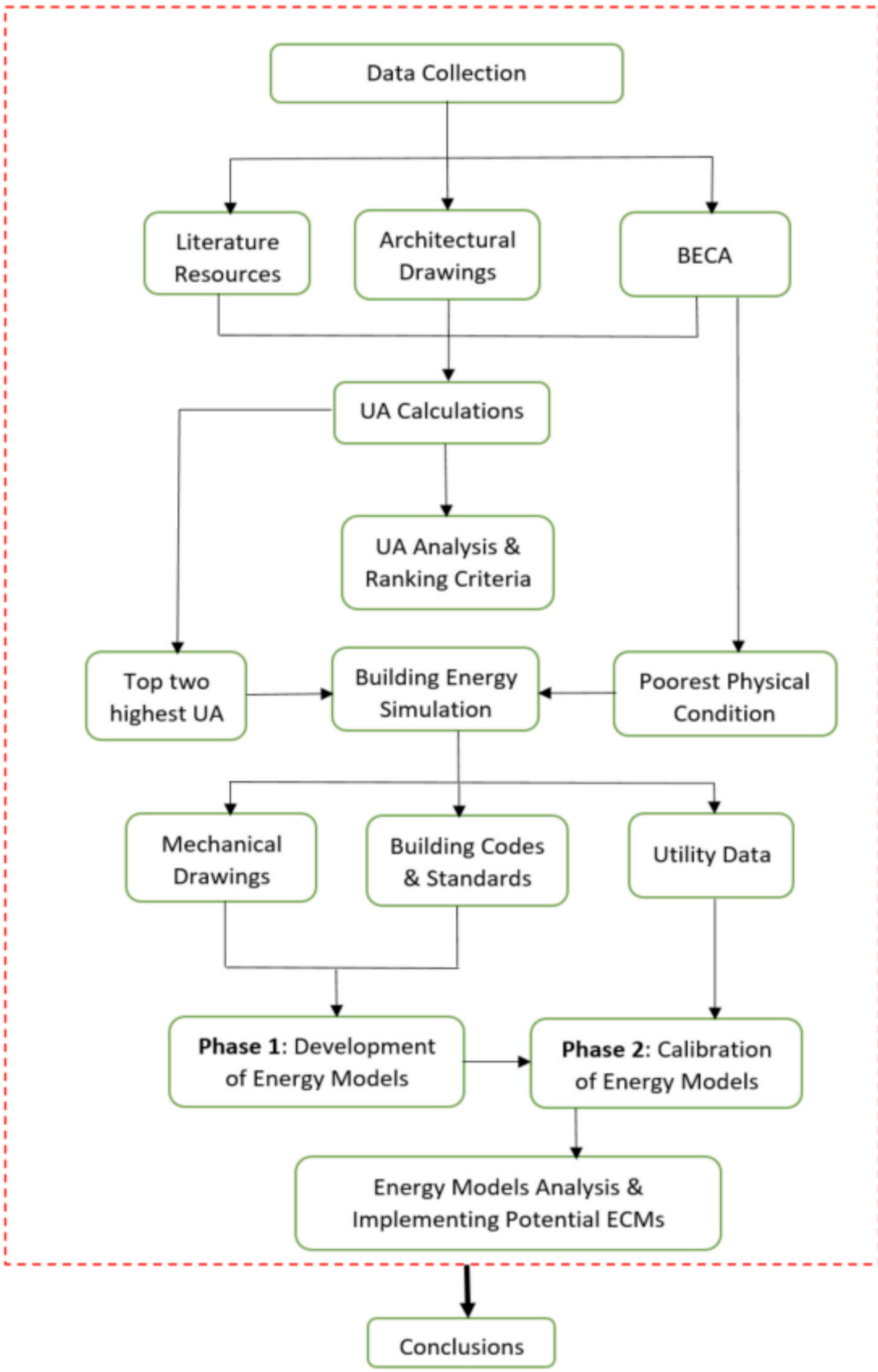

Fig. 1. Case study analysis flowchart.

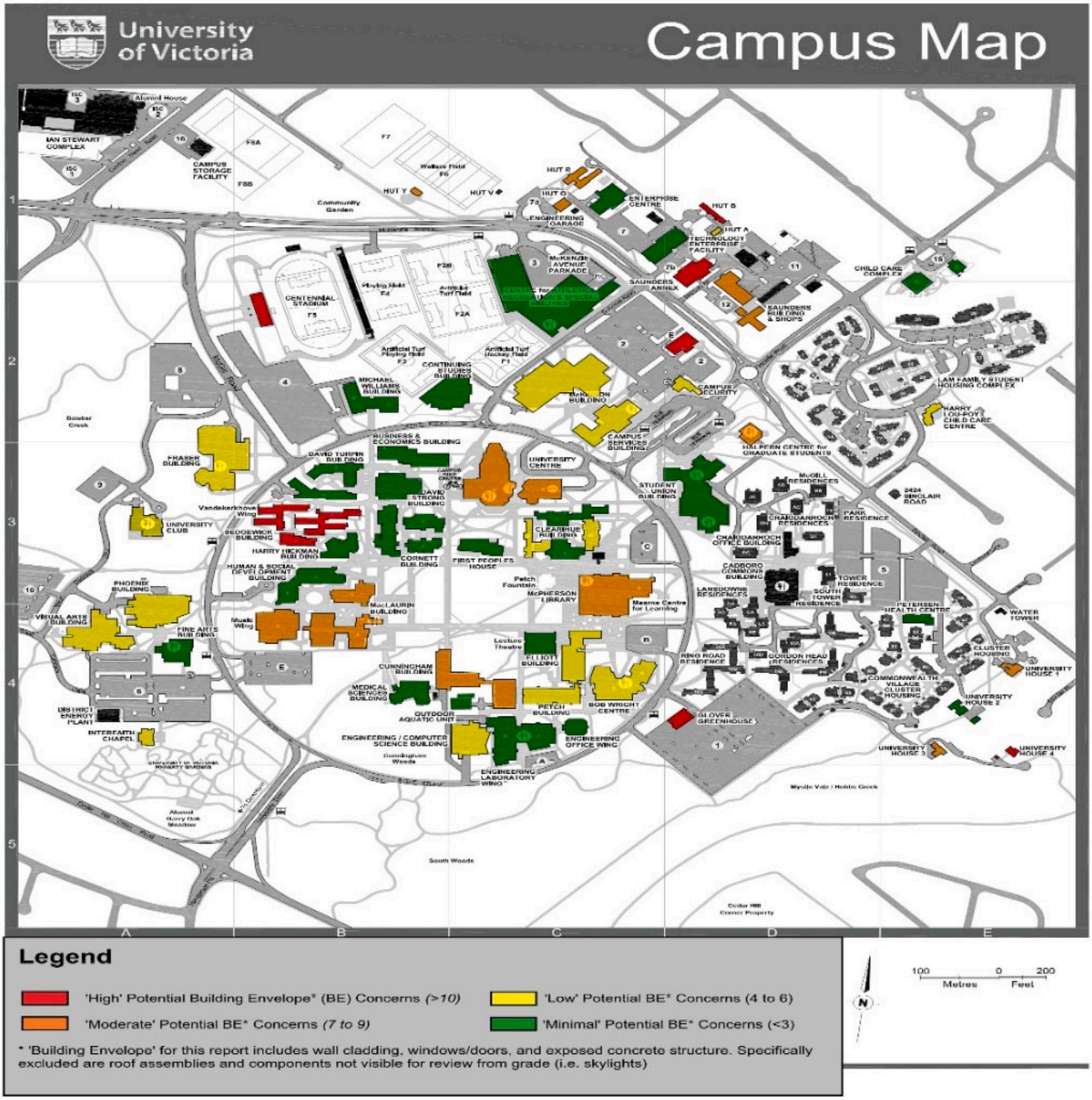

Fig. 2. Campus map (studied buildings depicted with colours). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Cooling on campus is limited to special utilities such as data centres and selected laboratories. There were some buildings which did not make sense to compare in the context of this study or were otherwise omitted from analysis. For instance, three buildings did not have enough information from available sources to warrant analysis, two were not heated and one was a greenhouse building with an intentionally high glazing ratio for growing vegetation.

To analyze high-level trends in the building portfolio, a variety of characteristics including age, construction type, size, space types and heat transfer coefficients were considered. It was found that older and smaller buildings were mainly wood framed, while newer and larger buildings were concrete framed with steel stud framed walls. Furthermore, offices buildings were largely wood framed while classroom and laboratory buildings were mostly concrete construction with steel stud framed walls. Finally, since envelope heat losses (both planar and linear contributions) depend considerably on their frame type, it was decided to categorize the buildings based on wood, steel stud, steel stud/concrete, and concrete wall assemblies. Building characteristics such as floor area (m^2), vertical building envelope area (m^2), window area (m^2), as well as age and space types are summarized in Table 1. The standard deviations of values in Table 1 demonstrate the variability of data that can be expected due to variations in architectural design trends and building codes over time.

Table 1
Buildings in the study (Mean ± Standard deviation).

Building Wall Frame type	Number of buildings	Building Characteristics				
		Floor Area (m^2)	Vertical Envelope Area (m^2)	Window Area (m^2)	Age (yrs)	Space types
Wood	19	883±675	664 ± 538	132±64	43±23	Office, clinic, lab
Steel stud	18	8037±4867	3954±2454	989±368	28±15	Office, lab, library, classroom, lecture hall, sport facility, food facility, theater space
Steel stud-concrete	10	9309±6816	4155±2516	1121±302	39±15	Office, lab, library, classroom, lecture hall
Concrete	2	6220±3650	4082±2785	1183±389	22±11	Office, lab

2.3. Overall vertical envelope heat loss (UA)

Overall heat loss (UA) calculations of vertical building envelope assemblies were based on heat losses through opaque (wall) and transparent (window) components as well as linear heat losses through thermal bridges obtained from simulation values in catalogues. An example of how to account for linear transition details with length and area takeoffs is presented in Fig. 3. It is to be noted that performing 3D simulation models for every single building based on real constructive elements requires complete architectural drawings. Given so many buildings are older, these details are often not shown on drawings but are otherwise detailed on site during construction according to the trades, as was customary during that era. Further, some drawing sets were not complete or otherwise missing for several buildings on campus. Knowing the construction industry only started to devote attention to mitigating thermal bridging in the mid-2010 era, the amount of thermal bridging expected at linear interface details is very predictable, as noted in the preface of the BC Hydro Building Envelope Thermal Bridging Guide [21], based on research formally vetted by peers in ASHRAE RP 1365 [38]. Hence, the increase in accuracy in assessing linear thermal transmittances with simulations will not affect the overall conclusions of the UA exercise or the energy model.

Furthermore, even 3D models based on the real constructive elements would certainly differ from their actual values since numerical models does not consider degradation of building materials, real moisture content, and errors associated with manufacturing. Hence, in-situ measurements tools (i.e. infrared thermography & heat flux meters) could be potential candidates to measure the actual U-values and linear thermal transmittances of building envelopes. However, in-situ measurement for large-scale evaluations of buildings is challenging and practically not feasible due to limitations in terms of time, cost and experimental set-up. Consequently, the focus of this study is to develop a rapid and robust approach that balances the effort required with obtaining practical direction or solutions.

Mathematically, the overall UA-value for any vertical building envelope section is expressed as:

$$(UA)_{overall} = U_{wall}A_{wall} + \sum(\Psi \cdot L) + \sum(\chi) + U_{window}A_{window} \tag{1}$$

Where:

- (U_{wall})is the clear field assembly thermal transmittance, estimated using ASHRAE 90.1-2010, Appendix A [39], Natural Resources Canada (NRCan) Tables for Calculating Effective Thermal Resistance of Opaque Assemblies [40], or the BETBG [21].
- A_{wall} and A_{window} are the areas of the opaque wall and windows, and $(L)$is the length of the thermal bridge, both measured with Bluebeam software from building architectural drawings.
- (Ψ) is the linear heat loss coefficient, which was obtained from simulation values in BETBG [21] and ISO 14683 [41] (Table 2). It is to be noted that for continuous exterior insulated assemblies, intermediate floor intersections were ignored. Also, corners were disregarded due to their small contributions to total heat loss.

Table 2
Linear heat loss coefficients based on the BETBG.

Thermal Bridge Type: Interface with Opaque Wall	Concrete/Steel Frame Assembly		Wood Frame Assembly	
	Ψ (W/mK)	Source	Ψ (W/mK)	Source
Ground Slab	1.0	BETBG Table 2	0.65	ISO 14683
Intermediate Floor	1.0	BETBG Table 2	0.12	BETBG 7.2.1
Fenestration	0.5	BETBG Table 3	0.24	BETBG 7.3.2
Parapet	0.8	BETBG Table 4	0.03	BETBG 7.4.2

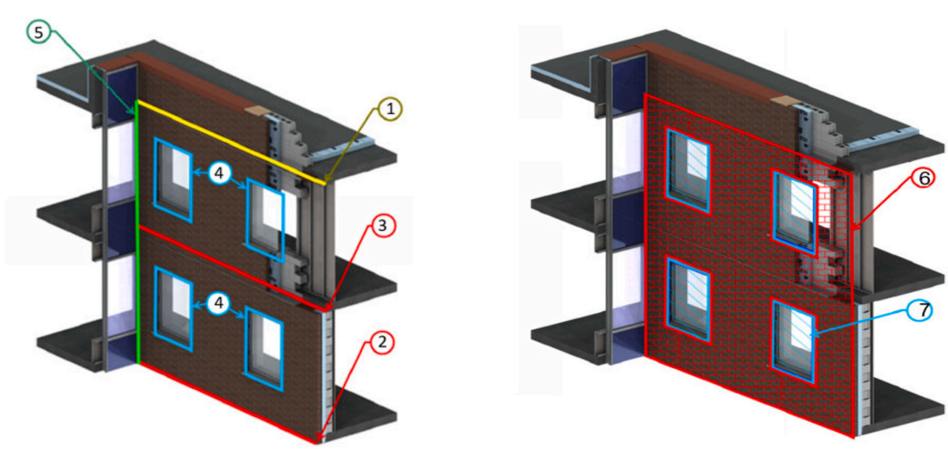

Fig. 3. Example of building length and area takeoffs: (1) Parapet length; (2) Slab lengths; (3) Intermediate floor; (4) Wall to window transition lengths; (5) Corner length; (6) Opaque wall area, and; (7) Glazing area [21].

- (χ) is the point source heat transmittance coefficients, which was disregarded in this study for simplification.
- (U_{window}) is the fenestration thermal transmittance, approximated from the ASHRAE Handbook of Fundamentals (2017) [35] according to their type (Table 3). Given the vintage of buildings, cavities in insulating glazing units (IGUs) for the majority of buildings were filled with air; additionally, glazing did not have low-e coatings, except for a select few newer buildings with triple and quadruple glazed windows.

3. Results and discussion

3.1. Correlations between envelope heat loss and building geometry

Building geometry often plays an important role in its overall energy efficiency. The parameters which were considered in this paper are: floor area, vertical envelope area, window to wall ratio (WWR) and vertical envelope area to floor area ratio (VFAR). Correlations between these parameters and overall thermal transmittance values were critically investigated. To this end, a statistical analysis based on Pearson's correlation was carried out using SPSS Statistics Software. A Pearson correlation (r-value) indicates the strength of linear relationship between two variables. It has a value between +1 and −1, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation. A normal distribution at 95% confidence level where the P-value is 0.05 was assumed in SPSS software. The P-value is the probability that indicates data did not occur by chance, and determines whether the correlation between variables is significant. If this probability is lower than 5% or 1% ($P < 0.05$; $P < 0.01$) the correlation coefficient is statistically significant, shown with * and ** symbols in Table 4, respectively. The results (r-values) are summarized in Table 4. To obtain the percentage variance, the square of the Pearson correlation coefficient (r^2) is multiplied by 100. The r-squared (r^2) value indicates to what extent the variance of a variable can be predicted by the variance of a second variable.

The results in Table 4 show that UA has a strong correlation with floor area ($r = +0.905$), where 81.9% (r^2) of the variance in UA can be attributed to a difference in floor area only. UA has an even better correlation with vertical envelope area ($r = +0.929$), where 86.3% of the variance in UA could be attributed to a difference in vertical envelope area only. It is also seen that vertical envelope area and floor area are linearly correlated ($r = +0.921$; $r^2 = 0.848$). Furthermore, results show that the normalized indices UA per unit floor area and UA per unit vertical envelope area have a modest linear correlation ($r = +0.705$; $r^2 = 0.497$). VFAR and WWR showed a poor linear correlation ($r = -0.472$; $r^2 = 0.222$). Finally, age appears to hold a moderate negative correlation with VFAR ($r = -0.433$; $r^2 = 0.187$), and a moderate positive correlation with WWR ($r = +0.413$; $r^2 = 0.171$), suggesting that older buildings have poorer (less efficient) geometry due to their smaller overall size less window area. Characteristics with significant relationships are presented in Figs. 4–7.

Fig. 4 depicts the results of the UA calculations as a function of useable floor area in the building. Wood framed buildings are generally smaller in floor area, while larger buildings are typically non-wood construction. Notably, a line of best fit through the data suggests there is a linear scaling of UA with increasing floor area regardless of building framing types, ages, and geometries. Hence, UVic may consider UA as one criterion for ranking thermal performance of building envelopes since both size and U-value are incorporated in this metric.

Table 3
Estimated thermal performance of fenestration.

Fenestration Type		U_{window} (W/m2K)
Single Glazed	Metal	6.5
	Non-Metal	5.5
Double Glazed	Metal	3.2
	Non-Metal	2.6
Triple Glazed	Metal	2.2
Quadruple Glazed	Metal	1.7

Fig. 5 shows the relationship of UA as a function of vertical envelope area for each of the buildings. The slope of the line of best fit represents the vertical area-weighted average U-value of the buildings studied. It is seen that wood framed buildings are mainly below the trend line, due in part to reduced impacts of thermal bridging. Wood has a lower thermal conductivity than steel or concrete, which in general results in lower thermal transmittance (U-value) assemblies, which can yield more energy efficient envelopes. Furthermore, from Figs. 4 and 5 it can be seen that UA values are more dependent on vertical building envelope area ($R^2 = 0.86$) than floor area ($R^2 = 0.81$). Therefore, vertical building envelope area can be a more representative characteristic in describing building envelope thermal performance on campus than floor area.

Fig. 6 describes the relationship between geometry and window area, represented by VFAR and WWR, respectively, for the buildings studied. It shows that wood framed buildings generally have higher VFAR (on average 0.80), and lower WWR, consistent with the age of the buildings (maximizing glazing area was not the focus of early 20th century building design. The Pearson correlation (Table 4) also confirms that age correlated with both VFAR and WWR. In general, non-wood framed buildings are larger and newer, have more stories, and therefore have a lower VFAR (on average 0.52). In practice, buildings with 'compact' geometries have a VFAR of 0.49–0.6, those with 'complex' massing including more articulations have a VFAR in the range of 0.59–0.72, and those with highly complex geometries are considered 'narrow' and have a VFAR of 0.7–0.86 [42].

From a practical standpoint, since building characteristics such as VFAR are not typically changed during its lifetime except where additions are made to the existing building, UVic should consider exploring a policy for a prescriptive maximum VFAR for new construction to help optimize building energy efficiency. Furthermore, where windows are approaching the end of their service life, buildings with high WWR should be prioritized for retrofit. These kinds of buildings have disproportionately poorer performance, even if they are newer (<15 years old) and have a good compactness (low VFAR). Prioritizing these buildings will also afford the opportunity to improve a more substantial length of window-wall transition detailing, reducing its associated thermal bridge, effectively resulting in a multi-beneficial upgrade.

Fig. 7 is a plot of UA per unit floor area versus UA per unit vertical envelope area. Wood-framed buildings have higher normalized UA per floor area due to higher VFAR. Normalizing a building's UA by its vertical area is a measure of its "average vertical envelope U-value". It can be observed that wood-framed buildings have a lower average U-value compared to other buildings on campus. This appears to be due to (1) wood-framed buildings on campus were generally older vintage with a much lower WWR (Fig. 6) than non-wood framed buildings, and (2) wood-framed buildings on campus are limited to a single story which excludes the thermal bridging penalty of intermediate floors. Also, it can be seen that the distribution of data in Figs. 4 and 7 are different, which can change prioritization rankings of buildings proposed to undergo envelope retrofits. For instance, based on normalized UA (Fig. 7), wood-framed buildings (small buildings) should be prioritized, while UA values (Fig. 4) suggest larger buildings are a priority. Both metrics are potentially useful for ranking buildings for envelope retrofits depending on priorities set out by University policymakers.

Table 5 is a summary of the data presented in Figs. 4–7. Notable observations are:

- By virtue of their age, even though wood framed buildings on campus have poorer geometry (i.e. high VFAR), they have a lower average U-value due to mitigated thermal bridging penalties.

Table 4
Pearson correlations between building characteristics (r-value).

Metrics	UA	UA/Floor Area	UA/Vertical Envelope Area	Floor Area	Vertical Envelope Area	WWR	VFAR	AGE
UA	1	-0.232	0.045	0.905**	0.929**	0.288*	-0.467**	0.105
UA/Floor Area	-0.232	1	0.705**	-0.362**	-0.337*	0.004	0.564**	-0.373**
UA/Vert. Envelope Area	0.045	0.705**	1	-0.055	-0.127	0.351*	-0.024	-0.113
Floor Area	0.905**	-0.362**	-0.055	1	0.921**	0.227	-0.543**	0.131
Vertical Envelope Area	0.929**	-0.337*	-0.127	0.921**	1	0.14	-0.456**	0.182
WWR	0.288*	0.004	0.351*	0.227	0.14	1	-0.472**	0.413**
VFAR	-0.467**	0.564**	-0.024	-0.543**	-0.456**	-0.472**	1	-0.433**
AGE	0.105	-0.373**	-0.113	0.131	0.182	0.413**	-0.433**	1

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

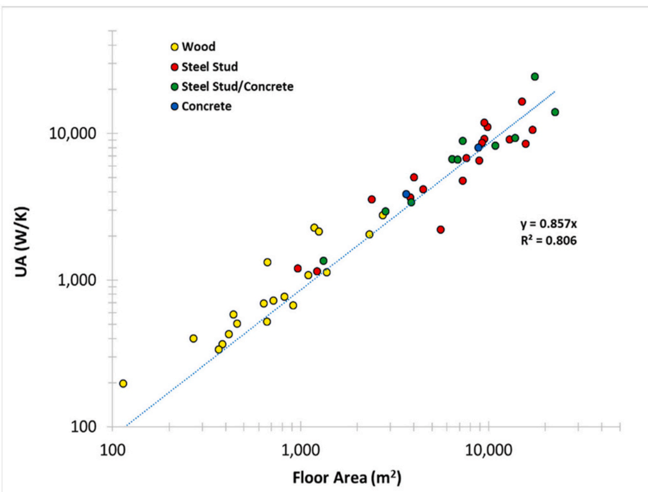

Fig. 4. Variation of UA with floor area.

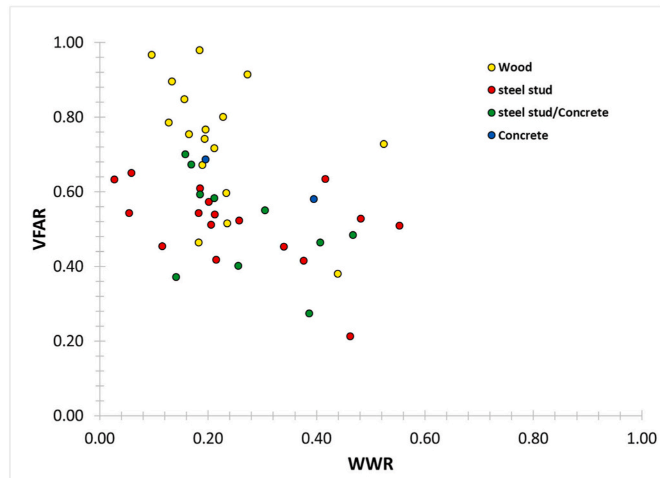

Fig. 6. Variation of VFAR with WWR.

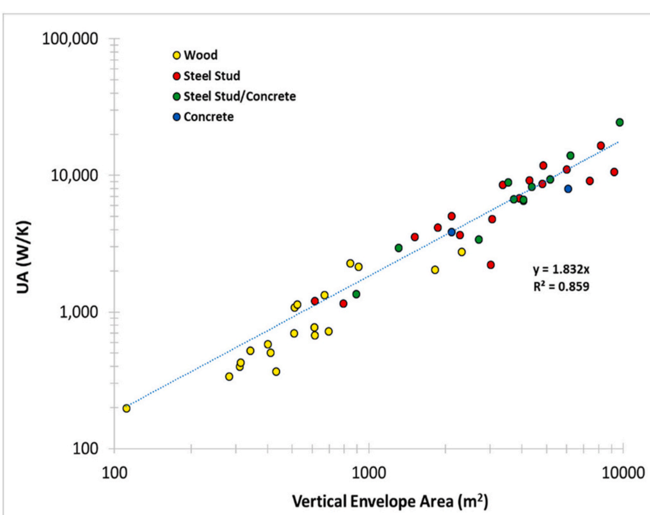

Fig. 5. Variation of UA with vertical envelope area.

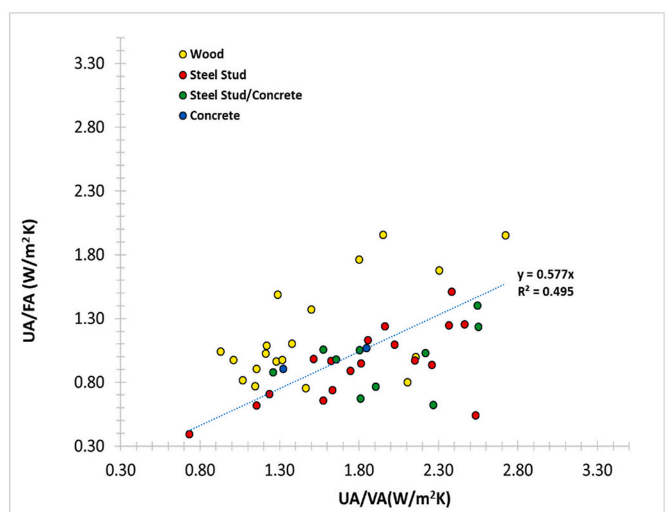

Fig. 7. Variation of UA per floor area with UA per vertical area.

- Based on floor area, wood framed buildings have a 50% higher normalized UA than other buildings, due mainly to a poor geometry (i.e. high VFAR).
- Absolute UA for wood framed buildings is much lower than other buildings, mostly due to their smaller overall size.
- Newer buildings, generally of non-wood construction, exhibited more efficient geometries (lower VFAR) due to additional storeys and were built in an era with an architectural predisposition to higher glazing ratios.
- NECB 2015 prescriptive U-values for walls are considerably lower than any building on campus, highlighting the relatively poor thermal performance of campus building opaque envelopes compared to current building code requirements in British Columbia. It should be noted that NECB 2015 does not require the inclusion of all thermal bridging effects in determining compliance with prescriptive U-values. Similarly, prescribed fenestration U-values in NECB 2015 are

Table 5
Performance of different structure based on various indices.

Wall Framing	UA (W/K)	UA/FA (W/m^2 K)	UA/VA Average (U-Value W/m^2 K)	VFAR	WWR	Floor Area (m^2)	Vertical Envelope Area (m^2)	Minimum Prescriptive NECB 2015 Average U-value[a] (W/m^2 K)
Wood (n = 19)	1000±768	1.18±0.39	1.53±0.50	0.80±0.21	0.20±0.12	883±675	664±538	0.39±0.06
Steel Stud (n = 18)	6939±4115	0.94±0.28	1.83±0.49	0.52±0.10	0.25±0.15	8037±4867	3954±2454	0.42±0.08
Steel Stud/Concrete (n = 10)	8630±6703	0.97±0.24	1.96±0.42	0.51±0.14	0.27±0.12	9309±6816	4155±2516	0.42±0.05
Concrete (n = 2)	5950±2899	0.99±0.12	1.58±0.37	0.63±0.07	0.29±0.14	6220±3650	4082±2785	0.43±0.07

[a] Calculated considering overall clear wall U-value 0.315 W/m^{2}K and window U-value 2.4 W/m^{2}K for Climate Zone 4.

lower than almost all buildings on campus, except for those with triple and quadruple glazed units.

The analysis illustrated how building envelope thermal metrics can be used as complementary criteria to rank buildings for retrofits, along with typology, size, age, and overall condition. Fig. 8 is a summary of various metrics analyzed for the portfolio of buildings in the study, and are based on building envelope thermal benchmarking and professional experience. The results are highlighted using a color bar scale based on percentile, where yellow represents the 50th percentile, red is the 100th percentile (highest priority), and green is the 0th percentile (lowest priority). In this case, buildings are ranked based on envelope heat loss (UA), but can otherwise be sorted by any other metric. Importantly, the results show that ranking of buildings by envelope heat loss (UA) yields different rankings than if the list was sorted by other metrics, similar to the findings when comparing rankings suggested by Figs. 4 and 7. It is seen there is no meaningful correlation between UA losses and condition score of buildings. For instance, DTB and COR are in the top five buildings with largest UA losses, while they are considered low risk by virtue of their condition score. In contrast, low envelope heat loss (UA) buildings like HTB and HTE are considered high risk in terms of their condition score. Additionally, some buildings with a high priority based on UA losses were largely categorized as low priority buildings in terms of normalized UA metrics (UA per floor area or UA per vertical area). Interestingly, newer buildings such as DTB, CARSA and ECS had high thermal losses (UA) due to a high WWR, high envelope area, and poor opaque wall performance, respectively, highlighting the importance of any one of these characteristics alone to absolute UA. Similarly, ranking buildings using other metrics such as age, wall framing type and average U-values yields different conclusions.

Given the focus on greenhouse gas (GHG) reductions per UVic policies, and that heating energy accounts for a substantial fraction of GHG emissions on campus, ranking building envelope performance with these metrics has practical merit for capital planning purposes. Ultimately, UVic's final decision will depend on a multitude of factors including capital costs associated with envelope retrofits (material & labour), programming requirements and limitations, achievable energy cost savings, and aesthetic benefits to name a few. Nonetheless, this type of analysis will facilitate the grouping and/or ranking of certain buildings versus others, streamlining the decision-making process.

3.2. Energy simulation

3.2.1. Phase 1: Initial development of energy models

Three buildings on campus were selected for energy simulation to quantify the economic impacts of envelope energy conservation measures (ECMs). Buildings were selected based on worst case scenarios where (1) all three selected buildings had a poor physical condition and required envelope upgrades, and (2) two of those buildings had the highest envelope energy losses (UA), and were among the largest and oldest buildings on campus. Since the established energy models are based on worst case scenarios and selected buildings have very different characteristics in terms of size, internal loads, space type, construction type, occupancy, and heating systems, the diversity of conclusions can inform decision-making for other campus buildings if they share relatively similar combinations of those characteristics; this is justifiable because utility costs, climate data, and carbon taxes are identical. Table 6 presents an overview of the studied buildings. Clearihue (CLE) and MacLaurin (MAC) have among the highest vertical envelope heat losses (See Appendices A2 & A3) and are also among the oldest buildings on campus that likely require envelope upgrades. The CLE building was one of the first large construction projects at the University of Victoria, completed in four stages ("wings") from 1965 to 1977. Since energy costs were relatively meager at the time of construction, little attention was devoted to building enclosure thermal performance or energy performance of heating and ventilation methods. Original windows have since been upgraded to double-glazed in aluminum frames throughout. Likewise, the MAC building was constructed in the late 1960s; however, only some windows have been upgraded from the original single glazed type.

Building energy simulations were performed using EnergyPlus v8.8, and for CLE and MAC, were based on archetype buildings due to their large size and number of rooms/zones. Archetype energy models are an effective representation of actual building energy models, accomplished by virtue of simplifying building geometry and grouping interior zones while assigning actual mechanical assumptions and internal loads. This simplification facilitates expediting model construction and simulation times for large buildings. In the archetype models developed for this study, each floor was divided into roughly 5 zones using the core/perimeter zoning strategy: four "perimeter" zones for each cardinal direction (i.e. north, south, east, west) and a "core" zone (see Fig. 9). A space within ~4 m of the façade on each cardinal direction was considered as a perimeter zone to capture the effect of zone solar gain at different times of day. Zones were grouped together roughly according to the predominant space type in each area.

Although Sedgewick (SED) was one of the lowest UA candidates, even among the lowest average envelope U-values, the building envelope condition assessment identified it as the most critically in need of an envelope upgrade (shown in red in Fig. 2). The SED facility was one of the first construction projects at the University of Victoria, completed as four separate buildings from 1968 to 2010. The buildings were originally intended to be temporary structures but have remained operational in part due to their unique and/or historic architectural appeal. Due to its small overall size, the SED building was modeled using actual zoning rather than archetype simplifications as in the other larger buildings. Building geometries were developed in SketchUp, integrated with an OpenStudio plug-in that translates information to EnergyPlus syntax. Building renderings are shown in Fig. 10.

The information available at the time of model construction included original architectural and mechanical drawings for each of the buildings. Access was granted to the UVic building automation system (BAS) to evaluate real operating conditions in terms of supply air and zone temperature setpoints and equipment schedules. For gas-heated buildings (CLE & MAC) the thermal energy is provided by the UVic central

Bldg	Frame	Overall UA (W/K)	Average of vertical envelope U-value (W/m²K)	Vertical Envelope Area (m²)	UA per Floor Area (W/m²K)	Floor Area (m²)	Year Built	Condition Score
CLE	steel stud/concrete	24,600	2.54	9670	1.40	17,537	1972	6
MAC	steel	16,500	2.02	8162	1.10	15,020	1978	9
LIB	steel stud/concrete	14,000	2.26	6181	0.62	22,473	1974	8
DTB	steel	11,900	2.46	4831	1.26	9,477	2008	2
COR	steel	11,100	1.85	5990	1.13	9,811	1966	2
CARSA	steel	10,600	1.15	9199	0.62	17,043	2015	2
ELL	steel stud/concrete	9,300	1.81	5143	0.67	13,803	1963	3
FRA	steel	9,200	2.15	4280	0.97	9,441	1980	5
BWC	steel	9,100	1.23	7374	0.71	12,849	2009	4
PCH	steel stud/concrete	9,000	2.55	3529	1.24	7,270	1984	5
BEC	steel	8,700	1.81	4803	0.95	9,169	1997	2
UVC	steel	8,500	2.53	3356	0.54	15,677	1978	9
ELW	steel stud/concrete	8,300	1.90	4357	0.77	10,832	1995	1
ECS	concrete	8,000	1.32	6052	0.91	8,801	2006	4
HSD	steel	6,800	1.74	3901	0.89	7,611	1992	3
CUN	steel stud/concrete	6,700	1.80	3715	1.05	6,361	1971	9
SUB	steel stud/concrete	6,700	1.65	4051	0.98	6,825	1962	3
MCK	steel	6,600	1.63	4042	0.74	8,892	1975	6
MWB	steel	5,000	2.36	2116	1.25	4,000	2008	2
CST	steel	4,800	1.57	3048	0.66	7,274	2003	2
CSR	steel	4,200	2.26	1860	0.94	4,474	1996	5
EOW	concrete	3,900	1.85	2112	1.07	3,639	1990	1
MSB	steel	3,700	1.62	2279	0.97	3,817	2003	2
FIA	steel	3,600	2.38	1512	1.51	2,378	1990	2
VIA	steel stud/concrete	3,400	1.26	2705	0.88	3,856	1992	5
TEF	steel stud/concrete	2,900	2.22	1308	1.03	2,817	2003	2
SED	wood	2,800	1.21	2312	1.03	2,725	1975	10
SAA	wood	2,300	2.72	845	1.95	1,178	1974	10
PNX	steel	2,200	0.73	3016	0.40	5,552	1981	4
FPH	wood	2,100	2.30	911	1.68	1,251	2010	2
SAU	wood	2,100	1.15	1819	0.91	2,312	1965	7
HHB	steel stud/concrete	1,400	1.57	890	1.06	1,321	1999	3
HTR	wood	1,300	1.95	667	1.96	664	1940	9
STA	steel	1,200	1.96	612	1.24	966	1974	10
EDC	steel	1,200	1.51	794	0.98	1,219	2009	1
CSF	wood	1,100	2.16	510	1.00	1,098	1989	5
UCL	wood	1,100	2.10	523	0.80	1,371	1982	5
UH1	wood	800	1.31	609	0.98	819	1969	7
GSC	wood	700	1.38	508	1.10	634	1990	7
CCC	wood	700	1.14	612	0.77	909	1993	1
HTE	wood	700	1.01	693	0.98	716	1992	10
CHA	wood	600	1.50	400	1.37	437	1984	6
HEA	wood	500	1.46	342	0.75	663	1969	1
SEC	wood	500	1.22	411	1.09	459	1996	4
HTB	wood	400	1.29	311	1.49	269	1940	10
HLP	wood	400	1.28	313	0.96	415	2001	6
HTQ	wood	400	0.93	431	1.04	383	1940	7
UH2	wood	300	1.07	281	0.82	367	2014	3
HTA	wood	200	1.80	111	1.76	113	1940	6

Fig. 8. Rank of buildings based on different criteria; color bar percentile scale from red (100th) to green (0th). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

gas-fired boiler plant for hydronic heating coils in air handling units (AHUs) and radiant hydronic terminal units. AHUs in CLE and MAC had economizers. SED was heated with electric-based systems (electric heating coils in AHUs and electric baseboards). Mechanical systems details are provided in Table 7.

Each building had a mix of space types identified in architectural drawings that were assigned approximately according to the archetype zoning in the model. Spaces in CLE included classroom, circulation

Table 6
Description of buildings studied.

Building	Floor Area (m^2)	Year Built	VFAR	WWR	Envelope construction	Heating Energy Source	Hot water	Space types
Clearihue (CLE)	18,115	1972	0.55	0.30	Steel stud/ Concrete	district hot water	gas-fired boiler plant	classrooms, offices, storage rooms, teaching labs, lounge, library, and a data centre
MacLaurin (MAC)	11,802	1978	0.54	0.18	Steel stud	district hot water	Electric	classrooms, offices, storage rooms, practice rooms, art studios, multiple main lobbies, teaching labs, a 300-seat lecture theatre, and a two-storey library
Sedgewick (SED)	3,003	1975	0.85	0.16	Wood	Electric	Electric	offices, storage rooms, mechanical room, staff lounge, boardroom, restrooms, library, and a crawlspace

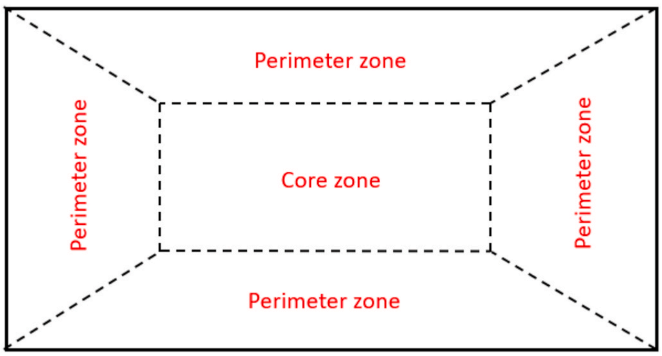

Fig. 9. Thermal zoning in archetype models.

(corridors & stairs), laboratory, library, lounge, office, mechanical, storage, and washrooms. MAC also included spaces defined as art studio, café, lecture theatre, and a large entrance lobby. SED had mostly office space, but also had boardrooms to facilitate meetings for administrative staff. Total areas of a particular space type in the model was approximately equivalent to its total area shown in architectural drawings. Internal loads such as lighting, occupants and plug loads were assigned according to the particular space type per unit area.

Fenestration was assigned to the model with an automated window wall ratio (WWR) script in Sketchup/OpenStudio. Both WWR and wall U-values (including the effect of thermal bridges, equivalent U-value) were obtained from the UA exercise in Chapter 3. It is to be noted that the effect of dynamic 3D thermal bridges and equivalent U-value (calculated in stead conditions) on the accuracy building energy simulations have been conducted in previous studies. The work done by Concordia University compares [43,44] the impact of dynamic thermal bridges on whole building energy-use for an archetype Canadian multi-unit-residential building, in climate zones 4 to 7. The results indicated that the higher the thermal mass the higher the differences between dynamic thermal bridge and equivalent U-value. However, for light-weight construction, i.e. wood-frame, and even heavy wood structures utilizing cross-laminated timber, the dynamic effect is not significant. The authors also suggested that with a decrease in the amount of thermal bridges (i.e. length or number) and by mitigating the heat loss through them (lower psi or chi values), the difference between utilizing the equivalent U-value and 3D dynamic modeling for energy modeling purposes decreases. From the conducted studies, it can be deduced that using linear thermal transmittance based on the BETBG to calculate the equivalent U-value in building energy models would not have a substantial influence on the conclusions obtained for buildings with steel-stud and wood-framed wall assemblies. Even in the case of heavyweight construction, dynamic thermal bridging is not a major consideration in a mild coastal climate. While the previous studies suggested deviations can be as high as 13%, results in the mild coastal Vancouver climate case for non-spandrel assemblies were significantly smaller (<5%), within acceptable limits of error in energy modeling in general [43,44]. Given these findings, the increased level of accuracy from dynamic simulations of thermal bridging was not warranted in this study.

Given limited information about installed lighting power and that the last major lighting retrofit was known to have complied with minimum code, lighting power densities (LPDs) were estimated based on the ASHRAE 90.1-2010 [39] space by space method. Plug loads, occupant densities, and all internal load and temperature setpoint schedules were based on NECB 2015 schedules corresponding to the space type. Air leakage, inclusive of manual "airing", was similarly assumed based on the NECB 2015 default value for building energy performance path (0.25 L/s/m^2 of exterior envelope area). Ventilation rates and

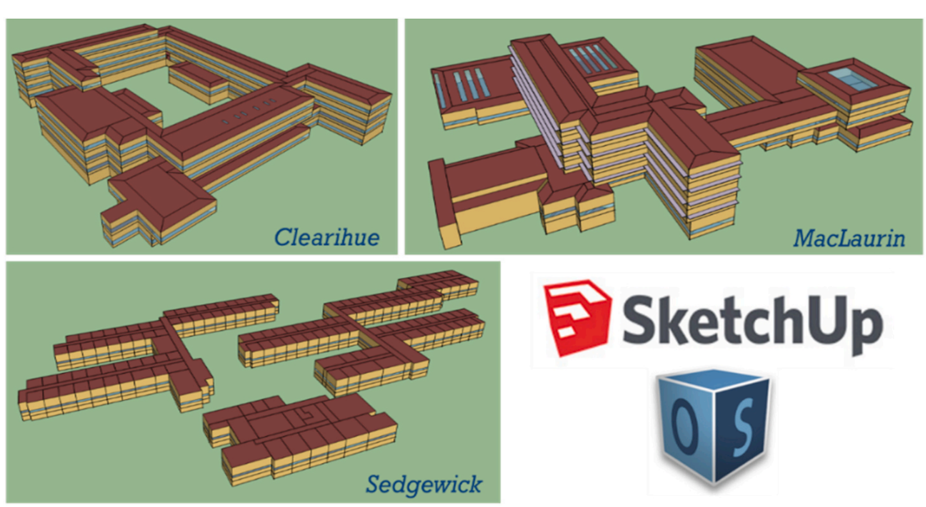

Fig. 10. SketchUp/OpenStudio renderings of modeled buildings.

Table 7
List of inputs for energy models.

Characteristic	Model Inputs		
	CLE	MAC	SED
Climate File	Victoria-Univ.of.Victoria.717830_CWEC2016, with 2,772 HDD (Base 18.3 °C)		
Infiltration	0.25 L/s/m^2 of exterior wall area, continuously	0.5 L/s/m^2 of exterior wall area, continuously (calibrated)	2 L/s/m^2 of exterior wall area, continuously (calibrated)
Plug loads	1 W/m^2: Library, Lounge, and Storage; 10 W/m^2: Classrooms; 15 W/m^2 Office and Teaching Lab (calibrated)	0.5 W/m^2: Lecture Theatre, Library, Lobby, and Storage; 10 W/m^2: Classrooms; 2.5 W/m^2 Office and Café (calibrated)	1 W/m^2: Library, Mechanical room, Restroom, Staff Lounge, and Storage room; 5 W/m^2: Office
Outdoor Air	4 ACH in all zones (calibrated)	Per ASHRAE 62.1-2001	Per ASHRAE 62.1-2001
Interior Lighting	Per ASHRAE 90.1-2010 (fluorescent lighting power density)	7 W/m^2 (calibrated)	8 W/m^2 (calibrated)
HVAC Systems	Constant volume systems with economizers; hydronic heating coils with terminal reheat and hydronic baseboards; hot water for heating coils supplied by natural gas district hot water plant Select classrooms with unit ventilators (dedicated outdoor air zone-level equipment with hydronic heating coil)	Constant volume systems with economizers; hydronic heating coils with terminal reheat and hydronic baseboards; hot water for heating coils supplied by natural gas district hot water plant Select classrooms and studios with unit ventilators (dedicated outdoor air zone-level equipment with hydronic heating coil) 7am-7pm weekday supply/return fan schedule	Constant volume system with electric heating coil and return air; all spaces include electric baseboard heating

mechanical system design were obtained from original mechanical drawings, and by cross referencing assumptions in the BAS where available.

3.2.2. Phase 2: Calibration of energy models

The energy models were calibrated based on measured energy data to represent actual performance, using ASHRAE Guideline 14–2014 [45]. The two uncertainty indices used in the calibration of natural gas and electricity were: (1) Normalized Mean Bias Error (NMBE) < 5%, and (2) the Coefficient of Variation of the Root Mean Square Error (CVRMSE) < 15%. The NMBE is a normalized MBE (Mean Bias Error). MBE is the average of the errors in a sample of data and is a good indicator of the behavior of simulated data. The NMBE is determined by diving MBE to the mean of measured values ($\overline{m}$). Equation (2) shows the correlation of NMBE where m_i is the measured value, s_i is the simulated data, n is the number of measured data points, and p is the number of adjustable model parameters, which for calibration is suggested to be zero [46].

$$\mathrm{NMBE} = \frac{1}{\overline{m}} . \frac{\sum_{i=1}^{n} (m_i - s_i)}{n-p} \times 100(\%) \tag{2}$$

CV (RMSE) measures the variability of the errors between measured and simulated values. It is obtained based on Equation (3), where the value of p is suggested to be 1 [43].

$$\mathrm{CV}\left(\mathrm{RMSE}\right) = \frac{1}{\overline{m}} \sqrt{\frac{\sum_{i=1}^{n} (m_i - s_i)^2}{n-p}} \times 100\left(\%\right) \tag{3}$$

The calibration process starts by adjusting one parameter at a time, running the EnergyPlus simulation, then comparing the simulated energy data with the actual energy data to determine whether the calibration criteria are met. If not, based on the deviation of the calibration pattern, the parameter is changed again or other parameters are adjusted. The calibration procedure continues until the calibration criteria of ASHRAE Guidelines 14–2014 have been met. Positive values in Equation (3) imply that the model under-predicts measured data, while a negative one implies over-prediction. Difference in calibration patterns indicate how different sets of model parameters should be adjusted during the calibration to minimize the deviation of the energy model from actual building operation [47].

Model inputs that were used for calibration included LPD, ventilation rate, and air leakage rate. Each building had a different strategy for calibration depending on how the initial model results compared to metered energy data. For example, given the mechanical systems were likely updated or re-commissioned a few times since the buildings were originally constructed, it was assumed that ventilation rates were updated according to ASHRAE 62.1 [37] as a starting point (higher than original drawings suggested). Ventilation rates were calculated from original mechanical drawings. For each AHU, the total rate of supply, return and exhausted air was calculated as a baseline ventilation rate. Systems were set up in the energy model serving the appropriate zones or building wings accordingly. Next, air leakage rates were adjusted to increase heating consumption in winter months, up to an order of magnitude higher than current code baselines. Finally, LPD was decreased to better match electricity consumption. Higher outdoor air rates were assumed (up to 4 ACH in the case of CLE) due to a combination of a better air barrier than other buildings, and higher lab/data centre space breakdown. A summary of model inputs is shown in Table 7.

It is worth noting that while internal loads influence the balance point temperature of the building, and consequently its heating demand, for the purposes of this study it was acceptable to use inputs from nationally recognized codes (i.e., NECB and ASHRAE 62.1, and ASHRAE 90.1) that are intended to be used for energy modelling purposes. In other words, since the energy data was provided for the archetype buildings and showed a clear seasonal (heating) variability, and because it is known that TEDI is accounted for primarily by air leakage, conduction heat transfer, and internal loads, the balance point temperature effect on envelope ECMs is not likely to have a demonstrable influence. While measuring air flow in air handling units would better inform air leakage assumptions in the energy model, it would nonetheless be confounded by the combined effect of occupant behavior with operable windows, versus the actual effect of air leakage. Therefore, a full blower door test (air leakage test) would be required to ascertain relative breakdowns of the above. To validate these inputs further would require a full ASHRAE Level II energy audit which was beyond the scope of the project, and would not increase the level of calibration accuracy to change any conclusions in the study; therefore, this level of calibration did not warrant the extra effort required to inform guidance for the University.

Even if the air leakage rates and mechanical ventilation rates were calibrated more accurately, the envelope's conduction heat transfer contribution to thermal energy demand intensity (TEDI) is independently known from UA calculations. In the case where envelope upgrades do in fact increase air tightness, it may cause unintended consequences to adequate ventilation rates for occupants. In this scenario, occupants may feel air quality is reduced, a condition which could trigger either a higher mechanical ventilation rate, or more frequent opening of windows: both conditions effectively would negate any potential energy savings from reduced air leakage rates by requiring an equivalent amount of heating energy. Therefore, for this kind of study in existing buildings, it is not professionally justifiable to claim air leakage savings with envelope upgrades alone.

3.2.3. Analysis of calibrated models

In order to evaluate the effects of energy conservation measures (ECMs) on the energy performance of buildings, it was necessary to obtain a case simulation model that represented the existing thermal behavior of the building as closely as possible. In this respect, the values of indices provided by ASHRAE Guideline 14 were calculated, as shown in Table 8. It is seen that NMBE and CVRMSE for electricity consumption were met for all buildings. Likewise, NMBE and CVRMSE for natural gas was met for CLE and MAC. Hence, it can be concluded that the models were calibrated within acceptable values determined by ASHRAE Guideline 14. Interestingly, even though more utility data was available for the SED building compared to CLE and MAC, the model for SED was more challenging to calibrate than CLE, possibly due to the fact that heating and equipment loads cannot be disaggregated in SED electrical utility data, as in the other buildings that are heated with gas only.

Fig. 11 is an illustration of monthly energy profiles in the buildings studied. Electricity data for CLE (Fig. 11a) was provided for the period of 2014–2018; however, only the data from 2014 was inclusive of all meters for each building wing. It can be observed that electricity consumption is higher in January to April than the model predicts, and lower in June to December. This could be explained by atypical occupant schedules as can be expected in University buildings where courses are structured by semester. Due to classes occurring during the summer semester, electricity consumption is still high during June–August. Furthermore, cooling load provided for the data centre as well as auxiliary equipment such as pumps result in higher electricity usage compared to the other buildings.

Substantially complete district hot water data was provided for 2018. Where data was missing over 1–2 weeks in two separate occurrences in February and April 2018, a reasonable estimate was calculated based on a simple extrapolation. Expectedly, district hot water consumption is larger during the heating seasons since the building is heated with natural gas (Fig. 11b). Heating water consumption in the model is overestimated in some months and underestimated in others, likely due in part to occupant schedule deviations from standard building code model assumptions.

Similarly, electricity data in MAC was manipulated to account for data gaps and to disaggregate data from main meters serving multiple buildings. District hot water data was provided from 2016 to 2018; where data was missing over 1–2 weeks in two separate occurrences in February and April 2018, a reasonable estimate was calculated based on a simple extrapolation. Fig. 11c shows that district hot water usage is substantially lower compared to CLE due to the smaller building size, and also because domestic hot water is served by electricity (unlike CLE). Moreover, variation in modeled results compared to actual data can be expected due to anomalous weather patterns over the last few years in Victoria. Similarly, variability in class and occupant schedules affects the monthly energy usage profile. Smaller deviations in monthly electricity consumption compared to district hot water can be explained by summer classes at UVic (see Fig. 11d).

Finally, calibration of SED was based on electricity data from 2014 to 2018 for the entire building, which is shown in Fig. 11e. It can be observed that the electricity usage pattern in SED is different with CLE and MAC during the summer, which can be attributed to its smaller size and that it is occupied only partially by full-time administrative staff (no students or large classes).

Table 8
Analyzing the magnitude of error between calibrated model and actual data.

Calibration criteria	Natural gas		Electricity			ASHRAE Guideline 14
	CLE	MAC	CLE	MAC	SED	
NMBE (%)	-0.06	-4.12	-1.51	-2.32	-4.33	±5%
CVRMSE (%)	0.22	14.85	5.24	8.04	15.00	15%

It is to be noted that the following mechanical assumptions in the energy model should ultimately be verified by means of an energy audit:

- total air flow rates
- fan motor specifications
- minimum outdoor air damper positions and behavior
- fan schedules
- office occupancies
- Intent of, and actual performance of, mechanical control strategies (demand control ventilation etc.)
- typical operation of operable windows by occupants

This information was not readily available in drawings or Building Automation System (BAS) data.

3.2.4. Impact of energy conservation measures on energy and cost savings

The calibrated energy models were used to evaluate the magnitude of energy and energy cost savings from potential building envelope and ventilation system retrofits. The strategies considered were: (1) improving window performance with a complete window replacement; (2) improving roof performance with added insulation; (3) improving wall thermal performance; (4) reducing the rate of air leakage; (5) Adding heat recovery of ventilation air with 70% efficiency. Strategies were analyzed based on two emerging building energy metrics in Canada:

- TEDI (Thermal Energy Demand Intensity): annual heating energy requirement from all types of space & ventilation heating equipment, per unit of modeled floor area.
- EUI (Energy Use Intensity): the sum of all energy used on site, minus all renewable energy generated on site, per unit of modeled floor area.

Costing assumptions are summarized in Table 9.

The results of the energy model analysis in Table 10 and Table 11 show that window/wall upgrades to modern standards have a relatively minor effect on TEDI and EUI, and an even smaller effect on utility cost savings (Figs. 12 and 13) due to: (1) a substantially larger fraction of energy consumed for heating of ventilation air; (2) relatively low carbon taxes; (3) relatively modest campus electricity rates, and; (4) a mild heating climate in Victoria, BC. Although retrofit measures in CLE and MAC did not have a major effect on energy efficiency, potentially improving the indoor environment quality (IEQ) for students is a more interesting perspective. For example, a better thermally performing envelope, either by way of lower thermal transmittance or reduced air leakage (or a combination of both), could make more of the floor area comfortable for occupants in perimeter zones like classrooms, offices, or labs, thereby maximizing classroom sizes. Combined with a re-designed interior design/layout and a re-commissioned mechanical system, IEQ could improve substantially.

In contrast, the analysis of the SED building (Table 12) illustrates that relative savings over the base case in TEDI (37%), EUI (26%), and annual utility cost (27%) start to become sizeable when considering the effect of upgrading the roof, walls, and windows (without addressing air leakage) (Fig. 14). It follows that because SED has a much higher 'narrow' VFAR of 0.84, it has much more conductive losses and therefore, will benefit from envelope upgrades preferably; in contrast, a lower VFAR means that there are fewer envelope losses and that internal loads such as lighting and occupants tend to dominate. Notably, energy cost savings are proportionally higher in an electrically heated building like SED (~$15,000 per year), likely due to a combination of higher cost of electricity relative to natural gas and poor base-case window performance, irrespective of the effect of the carbon tax.

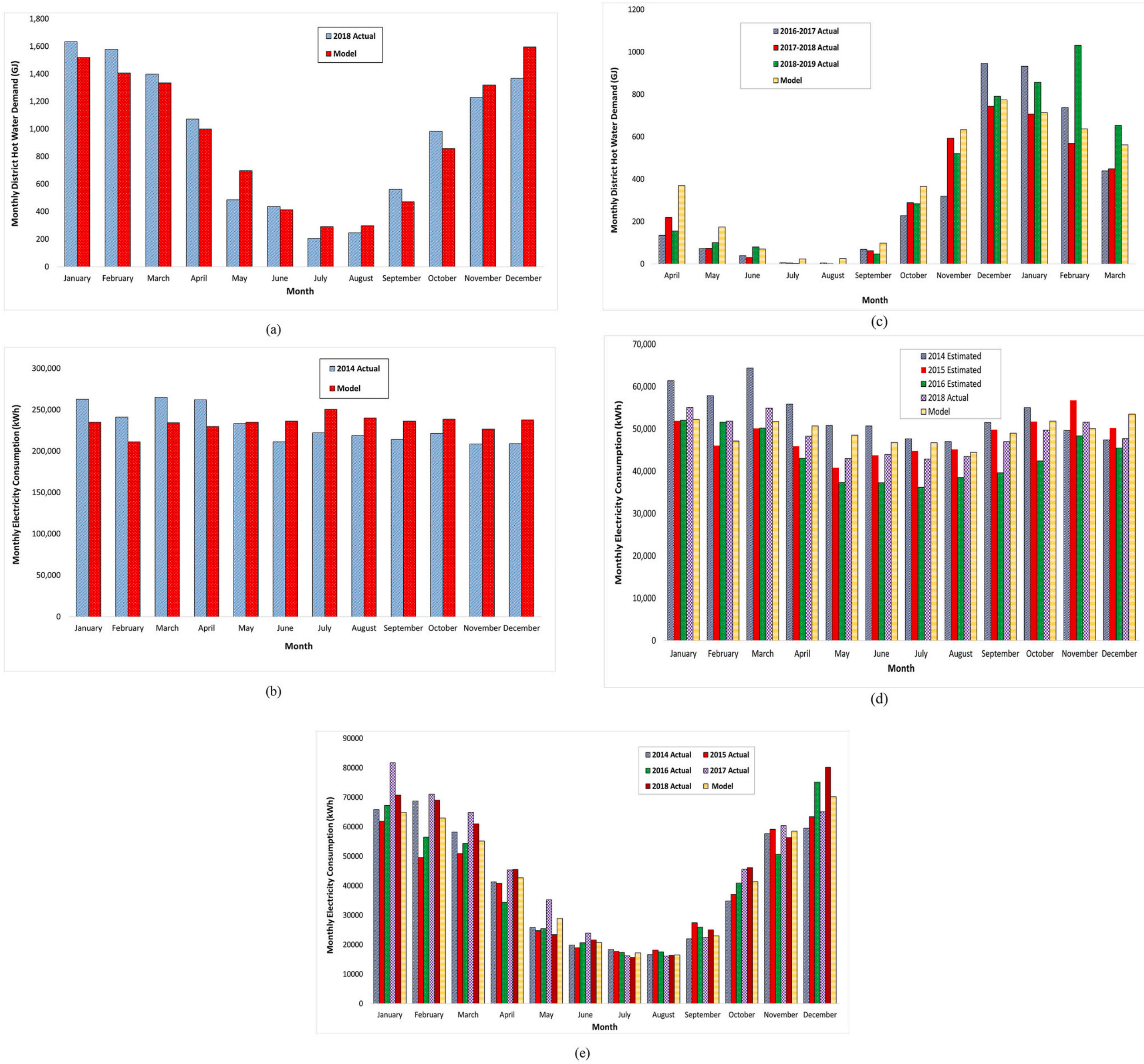

Fig. 11. Monthly Electricity Consumption and District Hot Water Demand of Modeled Buildings vs. Utility Data; (a) & (b) CLE; (c) & (d) MAC; (e) SED.

Table 9
Cost savings assumptions.

Costs	Rates
Electricity	\$0.064/kWh and \$12.56/kW monthly peak demand
Natural gas	\$7.88/GJ
	75% campus district hot water plant efficiency, accounting for combustion and distribution losses
Carbon Taxes	\$30/tCO$_2$e included in utility rates; Additional \$25/tCO$_2$e external tax; Currently no internal tax

Further, the last scenario in Table 12 demonstrates that if envelope upgrades can be coupled with mechanical heat recovery and a reduced air leakage rate there is a potential to realize almost 50% savings in EUI, more than 50% GHG reductions, and nearly a 70% reduction in TEDI. The EUI reduction was not as pronounced in CLE or MAC (last few rows in Tables 10 and 11) but was nonetheless significant. However, CLE had the biggest potential for low TEDI because of high ventilation heat recovery potential. It is worth noting that since the heat recovery system does not mix return air and fresh outdoor air, indoor air quality would likely improve with this system.

The cost implications of these potential upgrades would need to be investigated since applying these measures to existing buildings from this vintage and type of construction are not straightforward. For instance, adverse humidity generation indoors or too little ventilation rates in older buildings cause moisture problems. Hence, some older buildings rely on air leakage not only as a means of fresh air supply but also to allow the building to keep the envelope dry thereby mitigating condensation/mould risk. Adding exterior insulation could reduce air leakage prohibitively in this regard and trigger the need to introduce mechanical ventilation system(s). If air leakage is the only source of fresh air supply, it must not be restricted.

From the analysis, it can be deduced that buildings with similar envelope characteristics and archetypes as those modeled are likely to have similar TEDI, EUI, and GHG savings economics. Furthermore, it is recommended to prioritize the buildings heated with district hot water from the campus natural gas plant, since envelope retrofits are likely to have a dramatically higher GHG savings than electrically-heated

Table 10
Summary of energy modelling results for various ECMs for CLE building.

Scenario	Roof U-value (W/m^2 K)	Wall U-value (W/m^2 K)	Window U-value (W/m^2 K)	Air leakage in Mechanically ventilated zones ($L/s/m^2$)	HRE (%)	TEDI ($kWh/m^2/yr$)	EUI ($kWh/m^2/yr$)	GHG ($kgCO_2e/m^2/yr$)
Base case	0.57	2.54	3.2	0.25	0	162	384	43
Upgraded roof	0.19	2.54	3.2	0.25	0	159	380	42
Upgraded wall	0.57	1.49	3.2	0.25	0	159	379	42
Upgraded windows	0.57	2.54	1.8	0.25	0	156	376	41
Upgraded roof, wall & windows	0.19	1.49	1.8	0.25	0	150	368	40
Upgraded roof, wall & windows +70% HR & 50% less air leakage[a]	0.19	1.49	1.8	0.125	70	18	193	8

HRE: Heat Recovery Efficiency.
[a] Mechanically ventilated zones only.

Table 11
Summary of energy modelling results for various ECMs for MAC building.

Scenario	Roof U-value (W/m^2K)	Wall U-value (W/m^2K)	Window U-value (W/m^2K)	Skylight U-value (W/m^2 K)	Air leakage in Mechanically ventilated zones ($L/s/m^2$)	HRE (%)	TEDI ($kWh/m^2/yr$)	EUI ($kWh/m^2/yr$)	GHG ($kgCO_2e/m^2/yr$)
Base case	0.57	2.02	6.3 & 3.2	4.5	0.5	0	105	191	26
Upgraded skylights	0.57	2.02	6.3 & 3.2	3.2	0.5	0	104	191	26
Upgraded windows	0.57	2.02	1.8	4.5	0.5	0	100	185	25
Upgraded wall	0.57	1.14	6.3 & 3.2	4.5	0.5	0	100	184	25
Upgraded roof	0.19	2.02	6.3 & 3.2	4.5	0.5	0	99	184	25
Upgraded roof, wall, windows & skylights	0.19	1.14	1.8	3.2	0.50	0	89	169	22
Upgraded roof, wall, skylight & windows +70% HR & 50% less air leakage[a]	0.19	1.14	1.8	3.2	0.25	70	40	102	10

HRE: Heat Recovery Efficiency.
[a] Mechanically ventilated zones only.

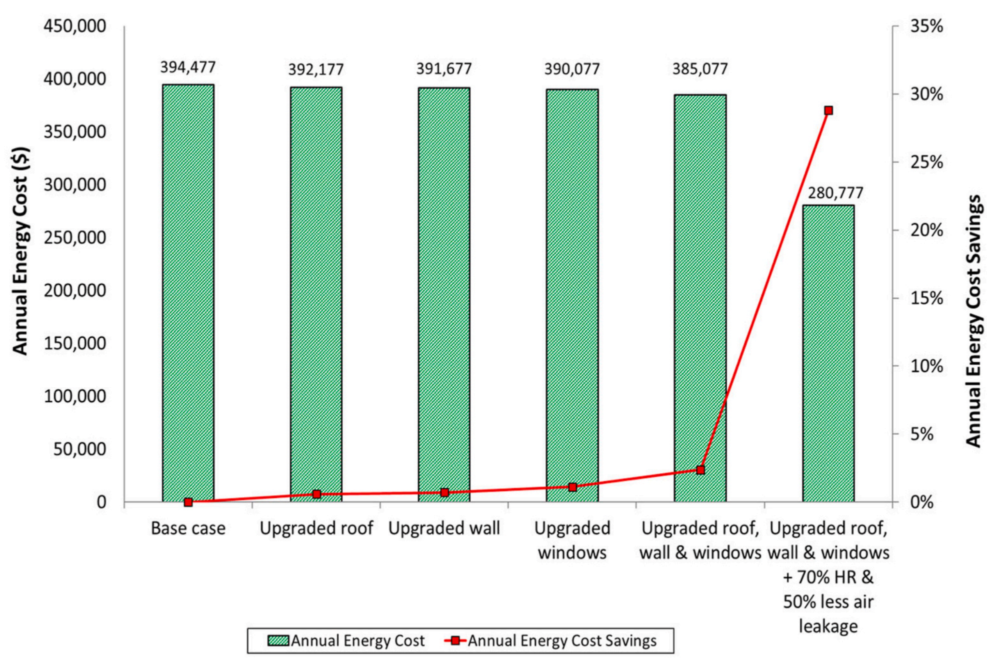

Fig. 12. Energy cost savings of CLE for different scenarios.

buildings. However, more attractive energy opportunities seem to be related to optimizing the mechanical (ventilation) systems of these buildings.

To illustrate from a different perspective, by analyzing three very distinctly different buildings in terms of shape, occupant profiles, construction type, and heating/DHW fuels, the study informed the university that buildings that share characteristics of one or more of those modeled would likely yield similar conclusions. For example, even if the wood framed Sedgewick building (SED) was heated with gas, the value of energy savings would smaller, GHG savings would be higher, but the overall conclusion regarding the poor value of envelope ECMs holds. Likewise, if the Clearihue (CLE) building was electrically heated, the value of energy savings due to envelope ECMs would be more attractive; however, per Figs. 12–14, the value of cost savings is on the order of ~

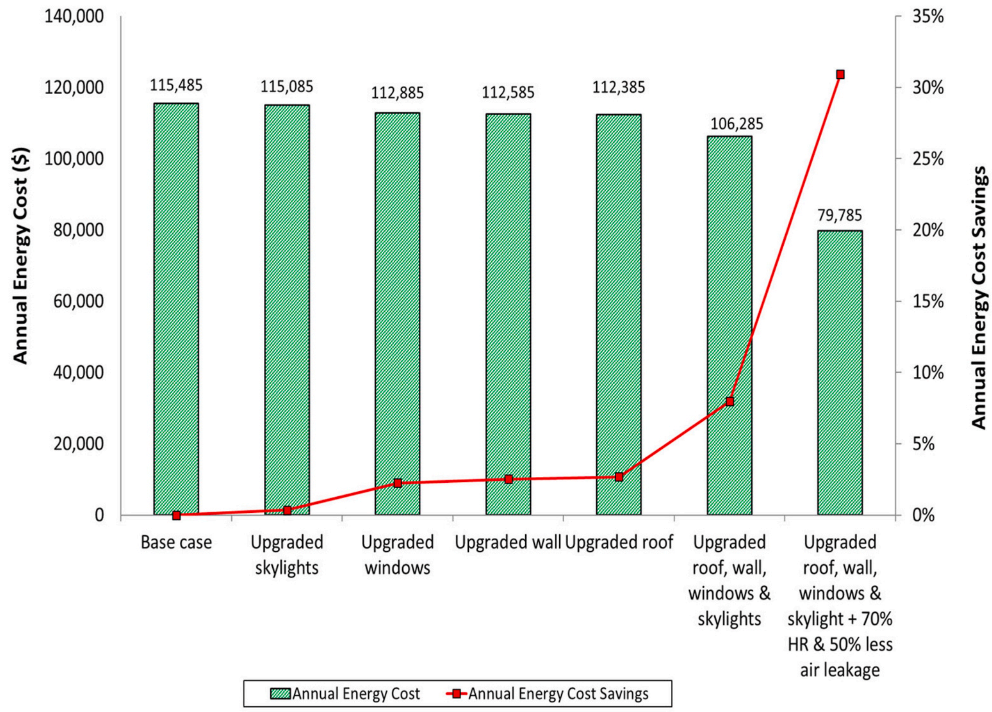

Fig. 13. Energy cost savings of MAC for different scenarios.

Table 12
Summary of energy modelling results for various ECMs for SED building.

Scenario	Roof U-value (W/m^{2}K)	Wall U-value (W/m^{2}K)	Window U-value (W/m^{2}K)	Air leakage in Mechanically ventilated zones (L/s/m^2)	HRE (%)	TEDI (kWh/m^2/yr)	EUI (kWh/m^2/yr)	GHG (kgCO_2e/m^2/yr)
Base case	0.52	1.21	2.8	2	0	116	165	2
Upgraded windows	0.52	1.21	1.8	2	0	112	161	2
Upgraded wall	0.52	0.57	2.8	2	0	106	156	2
Upgraded roof	0.19	1.21	2.8	2	0	89	138	1
Upgraded roof, wall & windows	0.19	0.57	1.8	2	0	73	121	1
Upgraded roof, wall & windows +70% HR & 50% less air leakage[a]	0.19	0.57	1.8	1	70	36	85	1

HRE: Heat Recovery Efficiency.
[a] Mechanically ventilated zones only.

$10k, which may be as high as ~17k in the best case scenario with electric heating assuming a 75% efficiency of heating water distribution on campus from the natural gas plant versus 100% in the electric resistance heating case, and the differences in fuel costs per Table 9. Given the suggested envelope retrofits would cost on the order of several millions of dollars according to the BECA, the overall message to the University remains the same in every scenario given the above examples:

- Envelope retrofits for an electrically heated buildings are more economically worthwhile than equivalent gas-heated buildings (cost-driven priority),
- Envelope retrofits for gas heated buildings have expectedly more substantial GHG reductions than equivalent electrically-heated buildings (carbon-driven priority),
- Neither scenario is economically justifiable for the university to take on as a project for the sole purpose of cost savings. Rates for electricity, gas, and carbon need to increase substantially to make the business case worthwhile. Retrofits should be prioritized based on other criteria, with energy/cost/GHG findings serving as complementary criteria.

Building energy metrics (TEDI and EUI) of the studied buildings were compared with proposed targets in the BC Energy Step Code Development for Public Sector Buildings [48] and the ASHRAE 100 [49] standard, shown in Table 13. It should be noted that ASHRAE 100 provides only EUIs target for several building typologies and does not consider TEDI metric for existing buildings. MAC and SED currently meet the ASHRAE 100 target for EUI, while CLE is well beyond it. This can be attributed to the fact that CLE has either much higher ventilation loads or a higher air leakage rate than the other buildings, and the significant electricity consumption used for the computers in the data centre, as well as the additional energy required for cooling it.

None of the buildings meet EUI and TEDI targets proposed for the BC Energy Step Code. Interestingly, although CLE can meet the TEDI target of BC Energy Step Code by implementing envelope upgrades coupled with mechanical heat recovery and a reduced air leakage rate, it cannot meet the EUI target, likely due to loads associated with data centre. MAC and SED were only able to meet the targets in the Energy Step Code in the best-case scenario of retrofit strategies.

In general, TEDI targets for all buildings identified in “BC Energy Step Code Development for Public Sector Buildings” can likely be achieved in these retrofits, but would require triple glazed fenestration and a better opaque wall system than our parametric analysis considered.

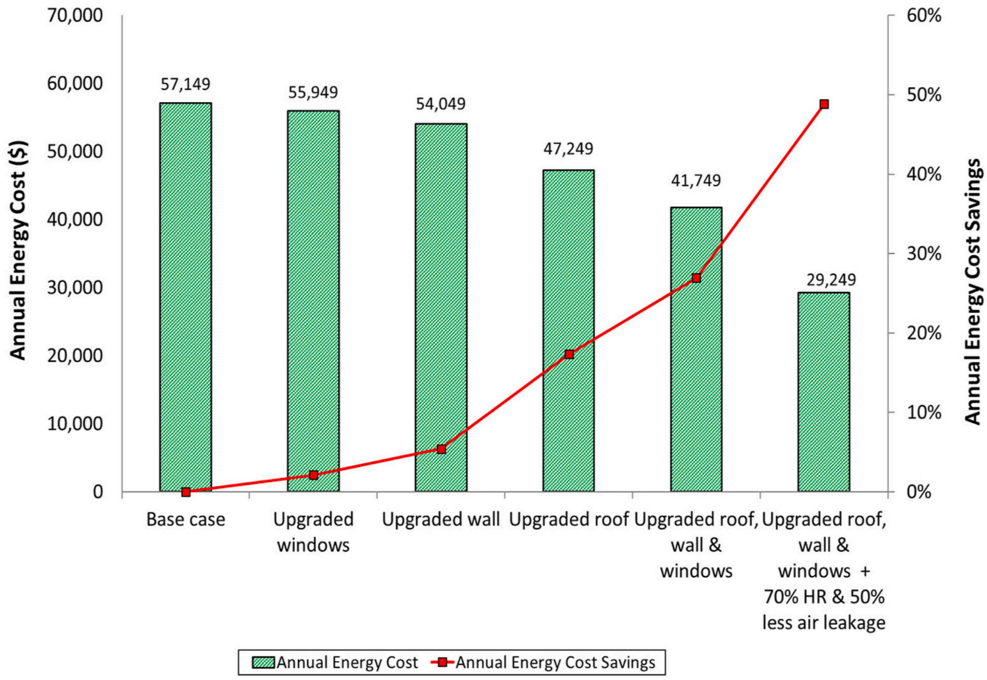

Fig. 14. Energy cost savings of SED for different scenarios.

Table 13
Contrasting EUI and TEDI of buildings in the study with the BC energy step code and ASHRAE 100.

Building	EUI (kWh/m^2/yr)	TEDI (kWh/m^2/yr)	Proposed Targeted EUI BC step-code (kWh/m^2/yr)	Proposed Targeted TEDI BC step-code (kWh/m^2/yr)	Targeted EUI in ASHRAE 100 (kWh/m^2/yr)
CLE	384	162	165	20	247
MAC	191	105	165	20	247
SED	165	116	130	30	193

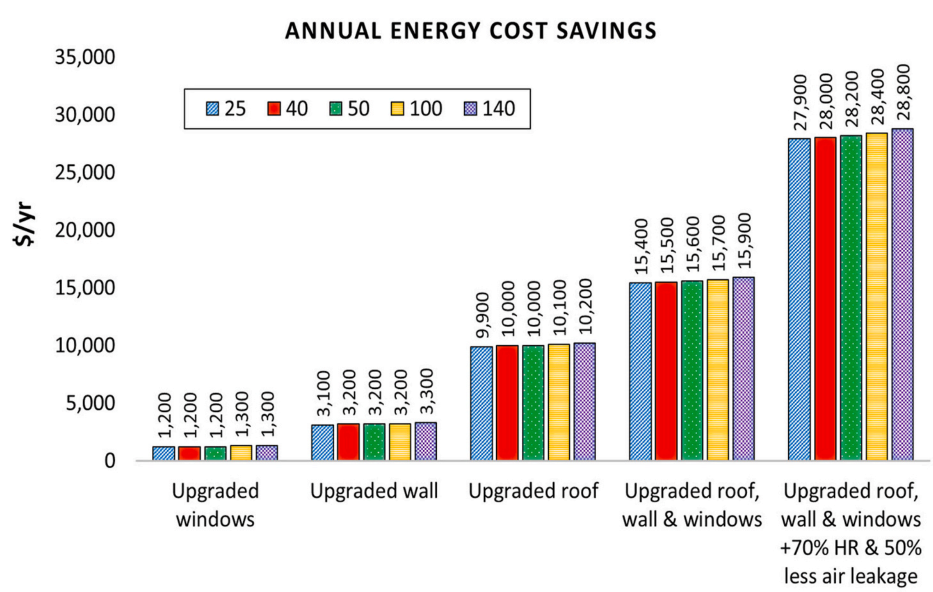

Fig. 15. Annual energy cost saving based on different scenarios of carbon tax ($/T-CO2e) for SED Building.

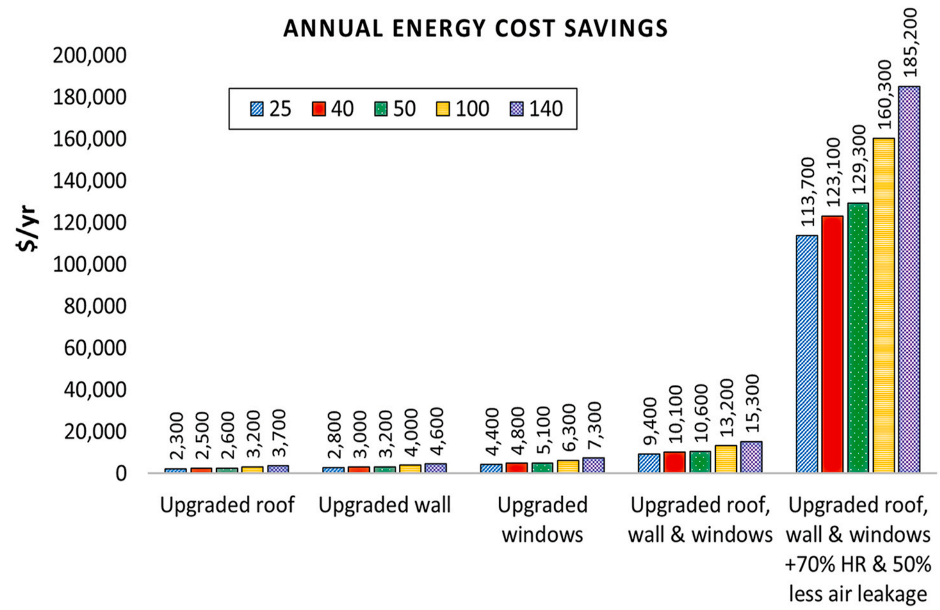

Fig. 16. Annual energy cost saving based on different scenarios of carbon tax ($/T-$CO_2$e) for CLE Building.

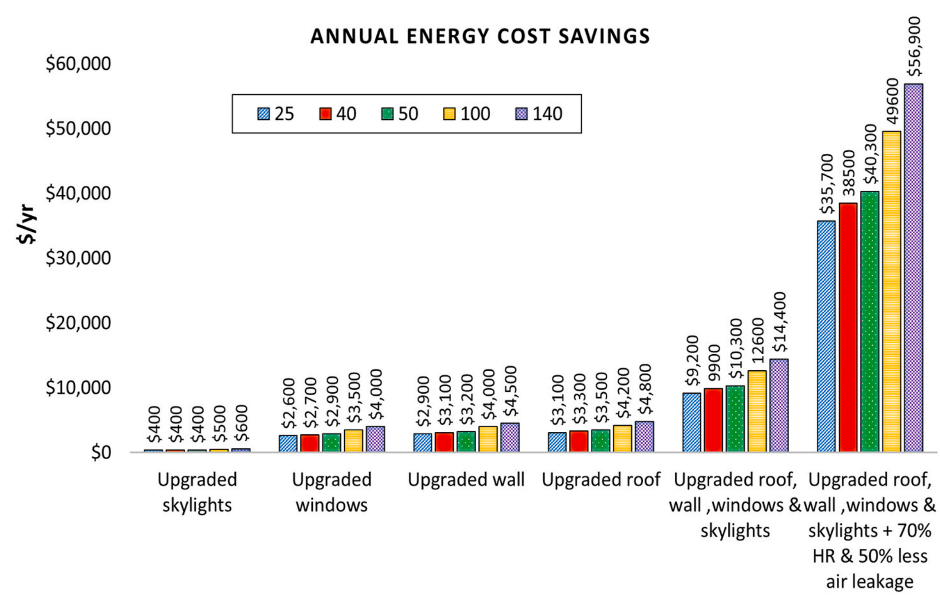

Fig. 17. Annual energy cost saving based on different scenarios of carbon tax ($/T-CO2e) for MAC Building.

Furthermore, achieving EUI targets will largely be dependent on TEDI reductions – lighting, plug load, fan, and pump savings cannot be stand-alone measures. Air leakage needs to be addressed for deep TEDI reductions, but as outlined earlier, it can be confounded by ventilation code implications.

Although retrofit strategies have a major impact on the energy reduction of buildings, energy cost savings is also often important. As mentioned above, energy cost savings were not considerable because of a low carbon tax price and Victoria's mild climate. To analyze the impact of carbon tax on annual energy cost savings, four other different carbon tax scenarios of 40 $/T-$CO_2$e, 50 $/T-$CO_2$e, 100 $/T-$CO_2$e and 140 $/T-$CO_2$e were analyzed. It should be noted that the 140 $/T-$CO_2$e is based on the highest rate of carbon tax in the world (Sweden). The results in Fig. 15 showed that the effect of an increased carbon tax had a relatively negligible effect on energy cost savings in electrically-heated SED. Conversely, as shown in Figs. 16 and 17, gas-heated buildings showed a more appreciable effect, up to 63% and 59% higher in the case of a 140 $/tonne carbon tax in CLE and MAC, respectively. Since the increase of carbon tax price influences the annual energy cost of gas-heated buildings substantially more than electrical heated buildings, the findings of this analysis inform the university that energy retrofitting measures should be implemented and prioritized for gas-heated buildings. Alternatively, gas heating systems could be replaced by electric-based systems to reduce annual energy costs in gas-heated buildings on campus.

It is to be noted that in British Columbia, the emission factor for electricity is very low (3.0 kg/GJ) as a result of 97% of the power generated by way of clean or renewable sources, a large majority of that accounted for by hydroelectricity. In contrast, the emission factor for natural gas is ~50 kg/GJ, a factor of 15x higher. Given these, increases to carbon taxes disproportionately affect natural gas rates relative to electricity rates by an order of magnitude or more. As a result of these points, increases in either gas utility rates, gas emission factors, or carbon taxes effectively increases the cost of gas consumption while negligibly affecting electricity costs. Therefore, in gas-heated buildings, building envelope retrofits yield better economic outcomes when any combinations of these gas variables are increased.

However, by increasing the cost of electricity in gas-heated buildings, the baseload (non-heating) energy costs will increase but does not affect the available cost savings from heating reductions. In contrast, in electrically-heated buildings, the overall cost of heating energy (and total energy) will increase and therefore presents a stronger business case for building envelope retrofits.

4. Conclusions

The building prioritization method for energy retrofit presented in this paper provided clear guidance to the University, as part of their ongoing capital plan, with respect to retrofits of existing building vertical envelopes. The implemented methodology and studied parameters unveiled a new horizon in evaluating the thermal performance of existing building envelopes in Canada, where a building code for existing buildings has not yet been established. This case study analyzed 49 buildings using a mixed methodology where building specific data was collected, and UA and other building metrics/characteristics were tabulated to provide added depth to the analysis. This was followed by a more detailed analysis using the energy simulation tool EnergyPlus on a few high priority buildings, and to a certain extent, conclusions from the detailed analysis could be applied to other similar campus buildings in Canada, and in particular British Columbia (where UVic is located), in which climate, construction practices, building codes, utility costs, carbon emission factors, and carbon taxes are similar to that of this study. The results from the building envelope condition assessment (BECA) provided yet another practical and complementary lens to recommendations from the energy efficiency perspective. The value of this study is in the development of a performance-based approach to optimize energy performance and cost effectiveness, in contrast to the simple traditional approach of prioritizing buildings based on their vintage or reference tables in building codes. The main findings of this study are outlined below:

- There was no correlation between physical condition and thermal performance of building envelopes in the building portfolio studied.
- Prioritization of buildings for envelope retrofits might be considered based on UA values if priority is given to the buildings with higher energy consumption.
- Normalized UA values with floor area or vertical envelope area is a better indicator of relative envelope performance than using absolute UA.
- Architectural characteristics such as VFAR and WWR have significant impact on the thermal performance of buildings. Buildings with higher VFAR have higher heat losses, and higher WWR not only increases thermal bridges, but also adds more of a higher U-value window area and subtracts a lower U-value wall area (“double penalty”).
- The results showed that wood framed buildings have lower U-values compared to the steel-stud and concrete framed buildings. This is justifiable from three perspectives:
  - o wood is a better insulator than steel or concrete; therefore, wood framed buildings have less thermal bridging losses.
  - o wood framed buildings on campus were generally older with a much lower WWR than larger non-wood buildings.
  - o wood framed buildings on campus are mainly limited to a single storey, and do not include the penalty of intermediate floor thermal bridges.
- Thermal bridging impacts are substantial in all buildings studied; building construction types or vintages do not seem to have significantly different U-values once all thermal bridging is accounted for.
- Since conclusions from ranking buildings based on one metric may not be consistent with ranking based on a different metric, multiple ranked lists should be considered in combination for building envelope retrofit decision-making. Policymakers or portfolio managers may decide to assign a higher priority to certain ranked lists versus others.
- Low campus utility rates, a low carbon tax, and a mild heating climate appear to be a barrier for most envelope upgrades (not considering air leakage effects).
- High VFAR and non-student occupied buildings have the deepest EUI reductions from envelope transmittance upgrades based on simulations.
- Deep reductions in TEDI, EUI, GHG, and utility costs are more likely to be achieved by a combination of reducing air leakage and implementing mechanical heat recovery of ventilation air.
- Buildings with similar envelope characteristics and archetypes as those modeled are likely to have similar TEDI, EUI, and GHG savings economics, highlighting the value of this hybridized analysis.
- Proposed energy benchmarks for college buildings in the “BC Energy Step Code Development for Public Sector Buildings” would be challenging to meet with a suite of envelope upgrades analyzed in this study. While the EUI benchmark is achievable, meeting the TEDI benchmark would require measures over and beyond those analyzed.
- Increasing carbon tax had a relatively negligible effect on energy cost savings in electrically-heated buildings. However, gas heated buildings showed a more appreciable effect, up to 63% and 59% higher in the case of a 140 $/tonne carbon tax in CLE and MAC, respectively.

To summarize, obtained results provided a practical perspective in the evaluation and ranking of a portfolio of buildings for envelope retrofits. The strength of the methodology was in its balance of effort and ultimate decision-making utility, where reasonable thermal bridging approximations for existing buildings can yield data accurate enough to inform a ranking exercise on a large breadth of subject buildings. Given that a large percentage of building stock (such as campus buildings) were constructed before the advent of building energy codes, and often have higher energy use compared to new construction, findings of this study could be used to inform effectiveness of energy policy at the provincial level for other buildings with similar characteristics. Furthermore, since targets for Thermal Energy Demand Intensity (TEDI) are limited only to new construction (i.e. residential, office, retail) in the current B.C. building code, the energy models developed in this study can pave the way towards informing TEDI targets for existing college/ university buildings. Considering the economic findings of the envelope retrofits studied, a government-mandated requirement (code) to improve existing building envelope performance would likely require additional incentive for building owners, such as higher utility costs, higher carbon taxes, or establishing government-funded incentive programs. It can be expected that as literature becomes more populated with such studies, more data will become available to establish existing building energy codes in the Canadian context.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix A1
List of studied Building

	BLDG	NAME	Frame	Built	Initial Description
1	BWC	Bob Wright Centre - Ocean, Earth and Atmospheric Sciences	steel	2009	offices, labs, lecture hall
2	BEC	Business and Economics Building & David Strong Building	steel	1997	Office/Faculty of Social Sciences
3	SEC	Campus Security Building	wood	1996	security offices, with power generator
4	CSR	Campus Services	steel	1996	bookstore, multifaith, offices, general store, cappucino bar
5	STA	Centennial Stadium	steel	1974	stadium facility
6	CARSA	Centre for Athletics, Recreation and Special Abilities	steel	2015	fitness/sports/world class facility
7	CHA	Chapel Building	wood	1984	chapel building for special events and multifaith services
8	CCC	Child Care Centre	wood	1993	child care with child activity rooms
9	CLE	Clearihue Building	steel stud/ Concrete	1972	humanities and technology solution centre (offices)
10	CST	Continuing Studies Building	steel	2003	continuing studies building (office/lecture?)
11	COR	Cornett Building	steel	1966	classroom, lab, faculty office for social science
12	CUN	Cunningham Building	steel stud/ Concrete	1971	animal care, aquarium, biohazard, electron microscope, etc
13	DTB	David Turpin Building	steel	2008	labs and offices
14	ELL	Elliott Building	steel stud/ Concrete	1963	3 storeys labs, 4 storeys office and research, lecture theatere, including observatory
15	ELW	Engineering Lab Wing	steel stud/ Concrete	1995	laboratories, computers/mechanical eng - "technologically advanced"
16	EOW	Engineering Office Wing	concrete	1990	labs and offices for engineering/robotics, energy, subsea, electromagnetics
17	ECS	Engineering/Computer Science	concrete	2006	offices, lecture halls, labs
18	EDC	Enterprise Data Centre	steel	2009	data centre; 3000 servers
19	FIA	Fine Arts Building	steel	1990	offices, classrooms, lecture hall, darkroom, lobby
20	FPH	First Peoples House	wood	2010	cermonial hall, elders rooms, classrooms, offices
21	FRA	Fraser Building	steel	1980	classrooms, seminar rooms, moot court
22	GSC	Halpern Centre for Graduate Students	wood	1990	multi purpose study rooms, restaurant
23	HHB	Hickman Building	steel stud/ Concrete	1999	lecture halls, smaller classrooms, seminar rooms
24	HSD	Human and Social Development	steel	1992	office, computer labs, classroom
25	HTA	Hut A	wood	1940	old WW2 army hut converted to office/lab
26	HTB	Hut B	wood	1940	old WW2 army hut converted to office/lab
27	HTE	Hut E	wood	1992	old WW2 army hut converted to office/lab
28	HTQ	Hut Q	wood	1940	old WW2 army hut converted to office/lab
29	HTR	Hut R	wood	1940	old WW2 army hut converted to office/lab
30	HLP	Lou-Poy Child Care Centre	wood	2001	infant/toddler daycare
31	MAC	MacLaurin Building	steel	1978	auditorium, recital hall, practice rooms, offices, recording studio
32	MCK	McKinnon Building	steel	1975	sports facility weight room dance, tennis courts, etc (now empty or repurposed)?
33	LIB	McPherson Library	steel stud/ Concrete	1974	Library
34	MSB	Medical Sciences Building	wood	2003	offices, lecture hall, lab
35	MWB	Michael Williams Building	steel	2008	Office
36	PCH	Petch Building	steel stud/ Concrete	1984	lab, office, lecture hall
37	HEA	Petersen Health Centre (PEA)	wood	1969	office/clinic
38	PNX	Phoenix Theatre	steel	1981	3 theatre spaces, and studio. Shop, rehearsal space, dressing rooms
39	SAA	Saunders Annex	wood	1974	facilities management - storage, shop, offices
40	SAU	Saunders Building	wood	1965	Offices
41	SED	Sedgewick Building	wood	1975	research centre and offices (mostly office)
42	SUB	Student Union Building	steel stud/ Concrete	1962	office, cafeteria, coffee shop, bookstore, travel agency, hair salon, lounge, movie theatre
43	TEF	Technology Enterprise Facility	steel stud/ Concrete	2003	offices, technology labs
44	UVC	University Centre	steel	1978	offices, food facility, auditorium
45	UCL	University Club	wood	1982	office, multipurpose dining/seminar
46	UH1	University House 1	wood	1969	offices in a single family home
47	UH2	University House 2	wood	2014	offices in a single family home
48	CSF	Velox Building	wood	1989	banquet hall, change rooms, storage, kitchen, dining
49	VIA	Visual Arts Building	steel stud/ Concrete	1992	classroom, office, studios

Appendix A2

Building Prioritization based on Façade UA Estimate; color bar percentile scale from red (100th) to green (0th).

Bldg	Frame	Façade UA Estimate (W/K)	Façade UA per Façade Area (W/m^2K)	Façade Area (m^2)	Façade UA per Floor Area (W/m^2K)	Floor Area Estimate from MH Takeoff (m^2)	WWR	VFAR	Year Built
CLE	steel stud/concrete	24,600	2.54	9670	1.40	17,537	0.30	0.55	1972
MAC	steel	16,500	2.02	8162	1.10	15,020	0.18	0.54	1978
LIB	steel stud/concrete	14,000	2.26	6181	0.62	22,473	0.39	0.28	1974
DTB	steel	11,900	2.46	4831	1.26	9,477	0.55	0.51	2008
COR	steel	11,100	1.85	5990	1.13	9,811	0.18	0.61	1966
CARSA	steel	10,600	1.15	9199	0.62	17,043	0.21	0.54	2015
ELL	steel stud/concrete	9,300	1.81	5143	0.67	13,803	0.14	0.37	1963
FRA	steel	9,200	2.15	4280	0.97	9,441	0.34	0.45	1980
BWC	steel	9,100	1.23	7374	0.71	12,849	0.20	0.57	2009
PCH	steel stud/concrete	9,000	2.55	3529	1.24	7,270	0.47	0.49	1984
BEC	steel	8,700	1.81	4803	0.95	9,169	0.26	0.52	1997
UVC	steel	8,500	2.53	3356	0.54	15,677	0.46	0.21	1978
ELW	steel stud/concrete	8,300	1.90	4357	0.77	10,832	0.25	0.40	1995
ECS	concrete	8,000	1.32	6052	0.91	8,801	0.20	0.69	2006
HSD	steel	6,800	1.74	3901	0.89	7,611	0.20	0.51	1992
CUN	steel stud/concrete	6,700	1.80	3715	1.05	6,361	0.21	0.58	1971
SUB	steel stud/concrete	6,700	1.65	4051	0.98	6,825	0.18	0.59	1962
MCK	steel	6,600	1.63	4042	0.74	8,892	0.11	0.45	1975
MWB	steel	5,000	2.36	2116	1.25	4,000	0.48	0.53	2008
CST	steel	4,800	1.57	3048	0.66	7,274	0.21	0.42	2003
CSR	steel	4,200	2.26	1860	0.94	4,474	0.38	0.42	1996
EOW	concrete	3,900	1.85	2112	1.07	3,639	0.39	0.58	1990
MSB	steel	3,700	1.62	2279	0.97	3,817	0.23	0.60	2003
FIA	steel	3,600	2.38	1512	1.51	2,378	0.42	0.64	1990
VIA	steel stud/concrete	3,400	1.26	2705	0.88	3,856	0.16	0.70	1992
TEF	steel stud/concrete	2,900	2.22	1308	1.03	2,817	0.41	0.46	2003
SED	wood	2,800	1.21	2312	1.03	2,725	0.16	0.85	1975
SAA	wood	2,300	2.72	845	1.95	1,178	0.21	0.72	1974
PNX	steel	2,200	0.73	3016	0.40	5,552	0.05	0.54	1981
FPH	wood	2,100	2.30	911	1.68	1,251	0.52	0.73	2010
SAU	wood	2,100	1.15	1819	0.91	2,312	0.13	0.79	1965
HHB	steel stud/concrete	1,400	1.57	890	1.06	1,321	0.17	0.67	1999
HTR	wood	1,300	1.95	667	1.96	664	0.11	1.00	1940
STA	steel	1,200	1.96	612	1.24	966	0.03	0.63	1974
EDC	steel	1,200	1.51	794	0.98	1,219	0.06	0.65	2009
CSF	wood	1,100	2.16	510	1.00	1,098	0.18	0.46	1989
UCL	wood	1,100	2.10	523	0.80	1,371	0.44	0.38	1982
UH1	wood	800	1.31	609	0.98	819	0.19	0.74	1969
GSC	wood	700	1.38	508	1.10	634	0.23	0.80	1990
CCC	wood	700	1.14	612	0.77	909	0.19	0.67	1993
HTE	wood	700	1.01	693	0.98	716	0.10	0.97	1992
CHA	wood	600	1.50	400	1.37	437	0.27	0.92	1984
HEA	wood	500	1.46	342	0.75	663	0.23	0.52	1969
SEC	wood	500	1.22	411	1.09	459	0.13	0.90	1996
HTB	wood	400	1.29	311	1.49	269	0.10	1.16	1940
HLP	wood	400	1.28	313	0.96	415	0.16	0.75	2001
HTQ	wood	400	0.93	431	1.04	383	0.00	1.12	1940
UH2	wood	300	1.07	281	0.82	367	0.20	0.77	2014
HTA	wood	200	1.80	111	1.76	113	0.18	0.98	1940

In this Table, the abbreviation of buildings was used. The full name of buildings can be obtained using: https://www.uvic.ca/search/maps-buildings/index.php.

Appendix A3

Building Prioritization based on Façade UA per Façade Area (Average U-Value); color bar percentile scale from red (100th) to green (0th).

Bldg	Frame	Façade UA Estimate (W/K)	Façade UA per Façade Area (W/m^{2}K)	Façade Area (m^2)	Façade UA per Floor Area (W/m^{2}K)	Floor Area Estimate from MH Takeoff (m^2)	WWR	VFAR	Year Built
SAA	wood	2,300	2.72	845	1.95	1,178	0.21	0.72	1974
PCH	steel stud/concrete	9,000	2.55	3529	1.24	7,270	0.47	0.49	1984
CLE	steel stud/concrete	24,600	2.54	9670	1.40	17,537	0.30	0.55	1972
UVC	steel	8,500	2.53	3356	0.54	15,677	0.46	0.21	1978
DTB	steel	11,900	2.46	4831	1.26	9,477	0.55	0.51	2008
FIA	steel	3,600	2.38	1512	1.51	2,378	0.42	0.64	1990
MWB	steel	5,000	2.36	2116	1.25	4,000	0.48	0.53	2008
FPH	wood	2,100	2.30	911	1.68	1,251	0.52	0.73	2010
LIB	steel stud/concrete	14,000	2.26	6181	0.62	22,473	0.39	0.28	1974
CSR	steel	4,200	2.26	1860	0.94	4,474	0.38	0.42	1996
TEF	steel stud/concrete	2,900	2.22	1308	1.03	2,817	0.41	0.46	2003
CSF	wood	1,100	2.16	510	1.00	1,098	0.18	0.46	1989
FRA	steel	9,200	2.15	4280	0.97	9,441	0.34	0.45	1980
UCL	wood	1,100	2.10	523	0.80	1,371	0.44	0.38	1982
MAC	steel	16,500	2.02	8162	1.10	15,020	0.18	0.54	1978
STA	steel	1,200	1.96	612	1.24	966	0.03	0.63	1974
HTR	wood	1,300	1.95	667	1.96	664	0.11	1.00	1940
ELW	steel stud/concrete	8,300	1.90	4357	0.77	10,832	0.25	0.40	1995
COR	steel	11,100	1.85	5990	1.13	9,811	0.18	0.61	1966
EOW	concrete	3,900	1.85	2112	1.07	3,639	0.39	0.58	1990
BEC	steel	8,700	1.81	4803	0.95	9,169	0.26	0.52	1997
ELL	steel stud/concrete	9,300	1.81	5143	0.67	13,803	0.14	0.37	1963
CUN	steel stud/concrete	6,700	1.80	3715	1.05	6,361	0.21	0.58	1971
HTA	wood	200	1.80	111	1.76	113	0.18	0.98	1940
HSD	steel	6,800	1.74	3901	0.89	7,611	0.20	0.51	1992
SUB	steel stud/concrete	6,700	1.65	4051	0.98	6,825	0.18	0.59	1962
MCK	steel	6,600	1.63	4042	0.74	8,892	0.11	0.45	1975
MSB	steel	3,700	1.62	2279	0.97	3,817	0.23	0.60	2003
CST	steel	4,800	1.57	3048	0.66	7,274	0.21	0.42	2003
HHB	steel stud/concrete	1,400	1.57	890	1.06	1,321	0.17	0.67	1999
EDC	steel	1,200	1.51	794	0.98	1,219	0.06	0.65	2009
CHA	wood	600	1.50	400	1.37	437	0.27	0.92	1984
HEA	wood	500	1.46	342	0.75	663	0.23	0.52	1969
GSC	wood	700	1.38	508	1.10	634	0.23	0.80	1990
ECS	concrete	8,000	1.32	6052	0.91	8,801	0.20	0.69	2006
UH1	wood	800	1.31	609	0.98	819	0.19	0.74	1969
HTB	wood	400	1.29	311	1.49	269	0.10	1.16	1940
HLP	wood	400	1.28	313	0.96	415	0.16	0.75	2001
VIA	steel stud/concrete	3,400	1.26	2705	0.88	3,856	0.16	0.70	1992
BWC	steel	9,100	1.23	7374	0.71	12,849	0.20	0.57	2009
SEC	wood	500	1.22	411	1.09	459	0.13	0.90	1996
SED	wood	2,800	1.21	2312	1.03	2,725	0.16	0.85	1975
SAU	wood	2,100	1.15	1819	0.91	2,312	0.13	0.79	1965
CARSA	steel	10,600	1.15	9199	0.62	17,043	0.21	0.54	2015
CCC	wood	700	1.14	612	0.77	909	0.19	0.67	1993
UH2	wood	300	1.07	281	0.82	367	0.20	0.77	2014
HTE	wood	700	1.01	693	0.98	716	0.10	0.97	1992
HTQ	wood	400	0.93	431	1.04	383	0.00	1.12	1940
PNX	steel	2,200	0.73	3016	0.40	5,552	0.05	0.54	1981

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