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Research Article

A simulation-based evaluation of the absolute and comparative approaches in a code compliance process from the energy use perspective: Cold-climate case study

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Abstract

Like many countries, Canada's building code includes a performance compliance path that compares the energy use of a proposed design to that of a reference house. Today, provinces across Canada are contemplating an alternative absolute energy use intensity approach. However, the effect of adopting the absolute approach on house design is not well understood. This study first developed a proof-of-concept methodology for a technical simulation-based comparison of the two approaches. Then, it performed a comparative analysis between the design outcomes of the two approaches using the developed methodology. To this end, statistically representative archetypes were configured to comply with the prescriptive requirements of the building code. Key characteristics of each archetype were then varied through parametric study, and the resulting energy performance under the absolute and comparative approaches were analyzed. The results of this study indicated that the two approaches had different effects on the design and energy use of houses in heating-dominated climate zones. Houses performing better under the absolute approach consumed less energy and exhibited more compact architectural form. These houses were also less sensitive to improvements in airtightness and envelope than houses performing better under the comparative approach. The results suggest that adopting the absolute approach based on the energy use intensity metric in building codes would encourage design and construction of houses with higher energy efficiency.

Keywords

performance path;
energy efficiency;
absolute target;
percent better than code;
reference building;
archetype

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1 Introduction

More than 30% of global energy use is in the building sector (IEA 2021a). This energy use is rising due to several factors such as growing use of electric appliances and higher space cooling with climate change (IEA 2021b). Building energy regulations play an essential role in reducing energy use in buildings through mandatory requirements (Nejat et al. 2015; Huang et al. 2016; Berardi 2017). Prior research worldwide has studied the role of building codes in reducing energy use (Tulsyan et al. 2013; Yu et al. 2014, 2017) and addressing global climate change (Enker and Morrison 2020).

Yet, policy makers may face challenges in implementing building energy codes effectively (Schwarz et al. 2020), leading to the performance gap between compliance and measured energy use (de Wilde 2014; van Dronkelaar et al. 2016). Functional implementation systems (e.g. compliance checks and evaluation, comprehensive code coverage) are important elements in achieving the full advantages of building energy codes (Evans et al. 2017).

Understanding the benefits and consequences of different code compliance metrics is a key step in establishing a functional implementation framework. Building energy codes offer different pathways for demonstrating compliance with mandatory requirements. By choosing a compliance path, a builder commits to design and construct buildings to meet a code's requirements associated with that path. Worldwide, building energy codes commonly provide two compliance pathways: (1) prescriptive path, and (2) performance path.

The prescriptive path regulates the quality and performance of individual components and systems of a building. For instance, the thermal resistance of a building's

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List of symbols

ABS	absolute analysis methodology
A_{floor}	total heated floor area (m^2)
Archetypes-ABS	archetypes perform considerably better under the absolute analysis methodology
Archetypes-CMPR	archetypes perform considerably better under the comparative analysis methodology
CMPR	comparative analysis methodology
CZn-ACH	archetypes simulated in the Canadian climate zone *n* with identical specifications but various airtightness levels
CZn-Baseline	archetypes simulated in the Canadian climate zone *n* with identical specifications
CZn-Wall	archetypes simulated in the Canadian climate zone *n* with identical specifications but various wall assemblies
CZn-Window	archetypes simulated in the Canadian climate zone *n* with identical specifications but various window assemblies
E	annual energy use (kWh)
$E_{Cooling}$	annual space cooling energy use (kWh)
E_{DHW}	annual domestic hot water energy use (kWh)
$E_{Heating}$	annual space heating energy use (kWh)
$E_{proposed}$	annual energy use of the proposed house (kWh)
$E_{Reference}$	annual energy use of the reference house (kWh)
EUI	energy use intensity (kWh/m^2)
$E_{Ventilation}$	annual space mechanical ventilation energy use (kWh)
HDD	heating degree-days (°C·days)
MEUI	mechanical energy use intensity (kWh/m^2)
nZEB	nearly zero energy buildings
TEDI	thermal energy demand intensity (kWh/m^2)
TEUI	total energy use intensity (kWh/m^2)

walls shall not be less than the values required by a code. Generally, the prescriptive path does not require energy calculations. Rather, builders need only adhere to minimum requirements relevant to each component and assembly in the building.

Whereas the prescriptive path disaggregates a building into its components and assemblies, the performance path is concerned with the performance of the whole building as a system. Building codes commonly use two analysis methodologies to evaluate energy performance: (1) comparing a proposed building's energy use to that of a reference building, and (2) comparing a proposed building's energy use to certain energy use targets. The former is called the comparative (also known as reference building or percent better than code) analysis methodology, and the latter is called the absolute analysis methodology (Karpman and Rosenberg 2020). Henceforth, the CMPR approach stands for the comparative analysis methodology and the ABS approach stands for the absolute analysis methodology.

In the CMPR approach, the estimated energy consumption of a proposed building is compared to that of the reference building. The reference building is a replica of a proposed building if designed to the requirements of the prescriptive path. The ABS approach compares a proposed building's estimated energy consumption to fixed energy targets such as total energy use intensity (*TEUI*).

Proponents of the ABS approach commonly cite three advantages: (1) more efficient building forms, (2) reduced code administration requirements, and (3) simplified comparisons between code cycles.

Under the CMPR approach, the reference building features similar geometry as the proposed design. Builders may choose articulated or elongated forms that increase envelope area relative to floor area, leading to higher energy use (Casals 2006; Arent et al. 2020). However, the ABS approach sets energy targets that are agnostic to building geometry, thereby encouraging builders to adopt more compact and more efficient designs.

Performance-based codes require code reviewers to verify a large number of inputs in each building model. Under the CMPR approach, the reviewer must check the inputs for two models: the reference building and the proposed design. The ABS approach eases submittal reviews because only one model need be inspected. These savings reduce the administrative burden of energy codes (Karpman and Rosenberg 2020).

The CMPR approach also complicates comparisons between different cycles of a building code. The reference building's characteristics are defined by the code's prescriptive requirements, and these requirements often change between each version of the code (Rosenberg and Hart 2014).

For these reasons, countries around the world have begun to adopt the ABS approach. Table 1 presents an overview of the various building energy codes' compliance approaches.

In Europe, Germany's EnEV regulates maximum whole-building's energy use and envelope's total equivalent thermal transmittance respecting buildings' size, shape, and local climate (Galvin 2010; Schettler-Köhler and Ahlke 2018).

Table 1 Comparing analysis methodologies adopted in various building energy legislation

	Analysis methodology		Energy performance		Opportunities			Challenges	
Legislation	ABS	CMPR	Whole building	Envelope	Considering contextual factors in defining target *EUI*-based metrics	Facilitating comparing the performance of a building with its peer buildings	Verification of compliance through measurement	Necessitating modeling reference building	Being sensitive to buildings use and operation assumptions
China's Quota Standard	✓		✓		✓	✓			✓
Germany's EnEV	✓		✓	✓	✓	✓			✓
Sweden's Building Regulations	✓		✓		✓	✓	✓		✓
Cyprus' nZEB legislation	✓		✓			✓			✓
France's nZEB legislation	✓		✓	✓		✓			✓
Italy's nZEB legislation		✓	✓					✓	
California's building energy efficiency standards	✓		✓		✓	✓			✓
ANSI/ASHRAE/IES Standard 90.1		✓	✓					✓	
ASHRAE/AIA/IES/USGBC/ DOE's AEDG	✓		✓		✓	✓			✓
Canada's NBC and NECB		✓	✓					✓	
BC Energy Step Code	✓	✓	✓		✓	✓		✓	✓
Toronto Green Standard v3.0	✓	✓				✓		✓	✓

Sweden's Building Regulations (BBR) sets the specific purchased energy use normalized by the floor area, as the energy used for space heating, domestic hot water, and facility appliances (Allard et al. 2017). The nearly zero energy buildings (nZEB) implementation in Cyprus sets target primary *EUI* for residential and non-residential buildings, whereas it sets target heating *EUI* for only residential buildings. The nZEB legislation in France also regulates target cooling and heating *EUI* as minimum thresholds. However, the nZEB prerequisite in Italy is that the energy performance of a building is better than the reference building (Attia et al. 2017).

In the USA, California's building energy efficiency standards (California Energy Commission 2019) evaluates buildings' performance using energy use intensity-based targets, called time dependent valuation energy use intensity (*TDV EUI*) for new construction. The sum of the *TDV* energy for space-conditioning, indoor lighting, mechanical ventilation, service water heating, and regulated process loads is calculated for the comparison between the proposed and standard design. *TDV* is the product of the site energy use and the *TDV* multiplier that is tailored to time of year, energy type, climate zone, and building type. The ASHRAE/AIA/IES/USGBC/DOE's (2018, 2019) advanced energy design guides (AEDG) for new school and office buildings also use *EUI*s (site and source *EUI*s) as absolute targets unlike ANSI/ASHRAE/IES 90.1's (2016) use of a percentage of energy reduction from a reference building. These AEDGs establish *EUI*s for various building types and climate zones using prototypical buildings. Similarly, China's Quota Standard defines the upper *EUI* limits for different building types and climate zones based on building energy use databases (Liu et al. 2019).

In Canada, the National Building Code (NBC) (CCBFC/NRC 2015) and the National Energy Code for Buildings (NECB) (CCBFC/NRC 2017) continue to use the CMPR approach for the performance path. However, the NBC and NECB are model codes in Canada. The federal government provides the NBC and NECB as a service to Canadian provinces and territories who have authority to write, enact, and enforce their own buildings codes. As such, provinces and territories may choose to adapt the NBC and/or NECB to local needs (NRCan 2020c). Indeed, the British Columbia (BC) Energy Step Code has introduced alternate performance compliance pathways based upon the ABS approach. Under this compliance pathway, the BC step code defines fixed energy targets for airtightness, mechanical energy use intensity (*MEUI*), thermal energy demand intensity (*TEDI*), and *TEUI* for NBC (CCBFC/NRC 2015) Part 3 and 9 (BC Housing 2018).

The Toronto Green Standard version 3.0 (TGS) (City of Toronto 2018) also requires that any submitted site plan control application complies with the standard based on one of the two ABS or CMPR approaches. As long as *TEUI*, *TEDI*, and greenhouse gas intensity (*GHGI*) for the type of a proposed building are available in the standard, the building (except for industrial buildings) must meet the absolute targets. Otherwise, the proposed building must perform at least better than its reference building. Replacing the Ontario Building Code's (Ministry of Municipal Affairs and Housing 2019) CMPR approach with the ABS approach, the TGS intends to push Toronto towards nZEB by 2030 (City of Toronto 2017).

As discussed above, the adoption of the ABS approach is regarded to be a more reliable performance path towards achieving more stringent building energy codes, nZEB, and closing the performance gap. Many countries around the world have started the adoption of the ABS approach in lieu of the CMPR approach for the performance path compliance.

As Canada moves towards more stringent energy codes, the question as to which approach will best serve the country remains unsettled. The current version of the NBC (CCBFC/NRC 2015) requires the CMPR approach for the performance path of the code. Recently, Codes Canada proposed changes to the NBC (CCBFC/NRC 2015) that would implement a tiered code based on the CMPR approach. However, during public review, numerous stakeholders advocated the ABS approach using *EUI*-based metrics (CCBFC 2021).

While the advantages of the ABS approach are known, there is a lack of understanding of the consequences of adopting the ABS approach on contemporary house design. Three questions remain unanswered: How much less energy will houses designed under the ABS approach use? Will the ABS approach favour larger or smaller houses? Will the ABS approach favour certain housing forms or features?

To address these gaps, the objectives of the present study are: (1) to develop a method for classifying contemporary houses designs according to whether they are favoured by the ABS or CMPR approaches, and (2) to contrast the characteristics and relative performance of these two types of houses.

This paper proposes a novel proof-of-concept methodology for comparing the energy performance of potential design outcomes of the ABS and CMPR approaches. While the study tests this method against the requirements of Canada's NBC (CCBFC/NRC 2015), the authors expect it to be relevant for studying the ABS approach in any jurisdiction that uses the CMPR approach.

The research questions of the current study are:

1. Do the ABS and CMPR approaches deliver identical design outcomes?
2. Adoption of which of the ABS and CMPR approaches leads to houses with higher energy efficiency?
3. What are the main characteristics of design outcomes of the two approaches?

The scope of this research is limited to residential housing as defined by NBC (CCBFC/NRC 2015) Part 9. This study focuses on houses' energy use as currently defined in the NBC (CCBFC/NRC 2015). Energy calculations accounted for space heating and cooling, water heating, ventilation, appliance and lighting end uses. However, the performance metrics computed in the study were limited to the regulated end uses under the Canadian building code—heating, cooling, hot water, and ventilation. This research is limited to the use of the *EUI* metric for the ABS approach rather than the determination of *EUI* targets for code compliance. Moreover, this research does not contemplate activities related to energy code enforcement, such as evaluation of building performance simulation (BPS) tools used for energy calculations.

2 Methodology

2.1 Classification of archetypes

For a comparative analysis between design outcomes of the ABS and CMPR approaches, this study proposes a novel method to classify archetypes according to whether they perform better under the ABS or CMPR approaches. Under this method, the two performance metrics of *percentage-better-than-code* and *EUI* (explained in Section 2.5) are calculated for each archetype in each climate zone. Based on the calculated *EUI*, archetypes are ranked in order of increasing *EUI* separately in each climate zone. The lower an archetype's position in ranking based on *EUI*, the higher the archetype's *EUI*. Similarly, archetypes are ranked in order of decreasing *percentage-better-than-code* separately in each climate zone. The lower an archetype's position in ranking based on *percentage-better-than-code*, the lower the archetype's *percentage-better-than-code*. Note that the developed method in the current paper ranks archetypes for the sake of classifying design outcomes of the ABS and CMPR approaches, rather than evaluating the energy performance of each individual archetype. Classification of the archetypes based on the two approaches facilitates the extraction of general characteristics of the cluster of design outcomes of the ABS approach in comparison with the cluster of design outcomes of the CMPR approach.

Once the *EUI*-based and *percentage-better-than-code*-based ranks of archetypes are found, the archetypes are categorized into three classes as follows:

- Class #1: An archetype falls into this class when the archetype's *percentage-better-than-code*-based rank increases by a factor of two in comparison with the archetype's *EUI*-based rank. These archetypes perform considerably better under the ABS approach.
- Class #2: An archetype falls into this class when the archetype's *EUI*-based rank increases by a factor of two in comparison with the archetype's *percentage-better-than-code*-based rank. These archetypes perform considerably better under the CMPR approach.

- Class #3: An archetype falls into this class when the archetype's *percentage-better-than-code*-based rank to the archetype's *EUI*-based rank is between 0.5 and 2. These archetypes do not perform markedly better under either the ABS or CMPR approach.

The current study focused on the comparative analysis between Classes #1 and #2 with respect to the research questions. Henceforth, the archetypes that fall into the first class are referred to as "Archetypes-ABS", and the archetypes that fall into the second class are referred to as "Archetypes-CMPR".

This study performed an independent-samples *t*-test to justify the proposed classification of archetypes. To this end, the mean annual energy use of the two classes (Archetypes-ABS and Archetypes-CMPR) were calculated and compared to determine if the mean values of the two classes were significantly different. The null hypothesis was that the two classes have identical mean annual energy use. The *p*-value of smaller than 0.05 rejected the null hypothesis. This statistical analysis showed that the mean annual energy use of the Archetypes-ABS and Archetypes-CMPR classes were significantly different at a confidence level of 95%.

Figure 1 presents a conceptual illustration of the Archetypes-ABS and Archetypes-CMPR classes. *EUI*-based ranks of the archetypes are plotted on the horizontal axis and *percentage-better-than-code*-based ranks of the archetypes are plotted on the vertical axis. A smaller value of an archetype's rank (i.e. towards the origin) is an indication of a higher energy performance of the archetype based on the ABS (horizontal axis) or CMPR (vertical axis) approach.

2.2 Archetypes

The classification method of the present study necessitates the use of a statistically representative sample size of the

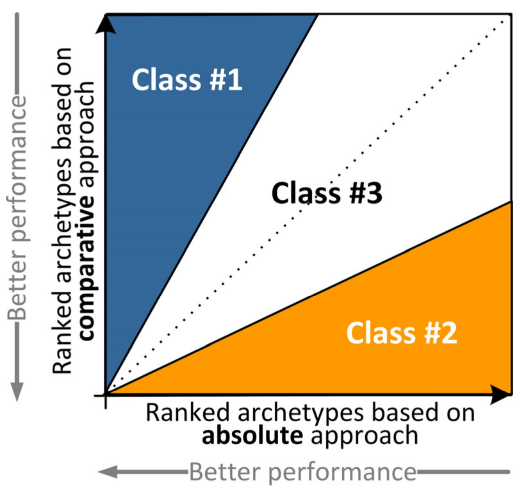

Fig. 1 Classification of archetypes based on the ranks they obtain under the ABS and CMPR approaches

contemporary housing. To this end, the study referenced a library of archetypes that Natural Resources Canada (NRCan) has developed by drawing data from the EnerGuide for Houses (EGH) program's database (Asaee and Ferguson 2018).

It is worth noting that EGH is NRCan's voluntary energy performance rating and labeling program. The Government of Canada supports this program to improve energy efficiency and comfort in houses while reducing greenhouse gas emissions (NRCan 2020b). A key aspect of the EGH program is that an energy advisor assesses a homeowner's house through field visits and the BPS tool HOT2000 (NRCan 2020a) to issue an EGH rating label for the house. The homeowner may also ask for an energy efficiency report to determine upgrades.

Since the start of the EGH program, a wide range of houses have been evaluated. Hence, detailed surveys of the Canadian housing stock have facilitated the development of housing characteristics libraries (Parekh 2005). These libraries consist of information about: (1) type, shape, size, orientation, and site specifications of houses, (2) envelope properties, (3) heating, ventilation, and air conditioning (HVAC) systems, (4) domestic hot water (DHW) systems, (5) occupancy, (6) baseloads (i.e. lighting, electric appliances), and (7) operating conditions.

Using the libraries, NRCan has developed a statistically representative sample of 240 Canadian houses archetypes based on statistical techniques (Asaee and Ferguson 2018). The archetypes have been drawn from real houses across Canada that were constructed between 2015 and 2018. This set of archetypes has four characteristics that are useful in the current study: (1) the houses represent contemporary Canadian construction, (2) they represent trends from different provinces and territories across Canada, (3) they include a variety of house types, and (4) they reflect common features found in residential construction today (Asaee et al. 2019). They include houses with one to three stories, single detached and attached or row houses, the floor area of 50 to 450 m^2 (Figure 2), and the foundation types of slab-on-grade, basement, walk-out, and crawl spaces.

2.3 Simulation tools

NRCan has created the open-source HOT2000 files of the archetypes by drawing data from the EGH program's database (NRCan 2019b). Disturbed by NRCan (2020d), HOT2000 is a key BPS tool used widely by building professionals across Canada for the evaluation of houses' energy performance. HOT2000 has been tested according to ANSI/ASHRAE Standard 140 (ANSI/ASHRAE 2014). Parekh et al. (2018) demonstrated the software produces acceptable results within the expected range for the whole building energy analysis.

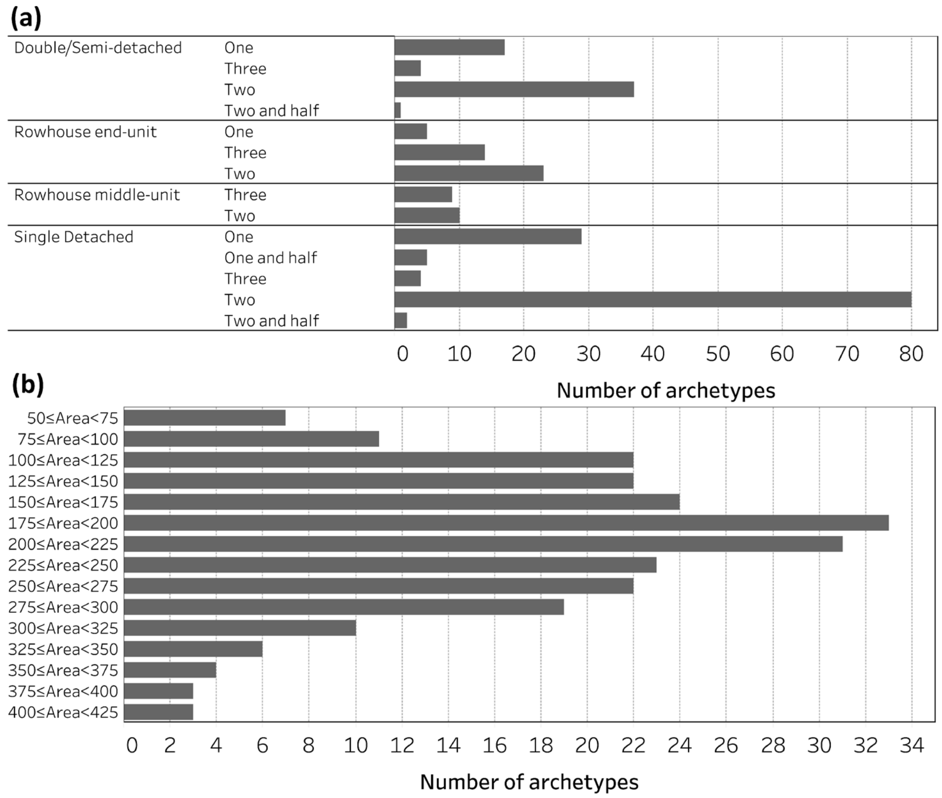

Fig. 2 Distribution of archetypes: (a) house type and number of storeys, and (b) floor area (m^2)

HOT2000 has been also validated against various energy simulation tools (Haltrecht and Fraser 1997; NRCan 2017).

The present study required a large number of HOT2000 simulation runs. To automate these batch simulations, the Housing Technology Assessment Platform (HTAP) (NRCan 2019a) was used. NRCan has developed the HTAP platform with the energy simulation engine HOT2000 using Ruby-based scripts to promote research and program development in the housing sector. Additionally, HTAP is being used for design optimization and impact analysis of retrofits and various technologies from energy and cost perspectives in the housing stock across Canada.

Using HTAP, multiple design options can be set for each attribute of the building model. The current design categories in HTAP are: (1) site specifications, (2) thermal specifications of foundation, walls, ceiling, windows, doors, and skylights, (3) airtightness, (4) HVAC systems, (5) DHW systems, (6) drain water heat recovery (DWHR) systems, (7) baseloads (including occupancy, use of lighting, electric appliances, hot water, and stove), and (8) heating and cooling setpoint and setback temperatures. Additionally, HTAP includes rulesets to automate reference house generation. In the current study, this feature was used to generate the reference house of each NRCan archetype as per the requirements set forward in Section 9.36.5 of the NBC (NRC 2015).

For each simulation run, each of the design options and rulesets are automatically replaced in the baseline (e.g. EGH archetypes). These features of the HTAP platform facilitated the simulation of all considered cases in the current study in parallel using the BPS tool HOT2000.

2.4 Reference and proposed houses

The reference house associated with each of the NRCan archetypes was simulated to evaluate the energy use of the archetypes based on the NBC (NRC 2015) requirements for the performance path. The requirement set of NBC's (NRC 2015) Section 9.36.5 was used within HTAP to simulate energy use of reference houses of the NRCan archetypes.

The current study used the NRCan archetypes as hypothetical proposed houses in a design process when the performance of a proposed house was assessed as per NBC (NRC 2015) Part 9. Note that all the archetypes that were originally located in various climate zones across Canada were all simulated in each climate zone. To this end, all the archetypes were simulated in the five cities listed in Table 2 as the most populous cities in each Canadian climate zones. Each archetype was simulated with four scenarios: (1) baseline (CZn-Baseline), (2) altered airtightness (CZn-ACH), (3) altered wall assemblies (CZn-Wall), and (4) altered window assemblies (CZn-Window) (Table 3).

Table 2 Definition of Canadian climate zones based on heating degree-days (HDD) with the base temperature of 18 °C, and the most populous city in each climate zone

Climate zone	HDD (°C·days)	City (winter design temperature °C)
4	< 3000	Vancouver (−7)
5	3000–3999	Toronto (−20)
6	4000–4999	Montreal (−23)
7A	5000–5999	Calgary (−30)
7B	6000–6999	Whitehorse (−41)
8	≥ 7000	Yellowknife (−41)

The baseline of all the archetypes was simulated using the envelope properties and HVAC and DHW systems, as summarized in Table 4. Windows were equally distributed on all sides of the archetypes. Operation schedules and heating and cooling setpoints were set based on the NBC (NRC 2015) (Section 9.36.5). All the archetypes were simulated with identical site specifications and baseloads (using the EGH program's standard operating conditions). None of the archetypes included DWHR and HRV systems to exclude the energy savings from DWHR and HRV systems in the calculation of annual energy use of the archetypes.

In addition to the baseline, each archetype was simulated with a set of airtightness levels and wall and window assemblies for the envelope parametric study. The considered alterations were simulated by changing each parameter (i.e. airtightness, walls, and windows) one at a time. When a considered parameter changed, all other parameters were simulated similar to the baseline's assumptions (Figure 3).

Note that once each of the NRCan archetypes was simulated with various envelope design options in each climate zone, the two performance metrics of *percentage-better-than-code* and *EUI* (explained in Section 2.5) were calculated for each design case. Afterwards, under each scenario (i.e. CZn-Baseline, CZn-ACH, CZn-Wall, and CZn-Window), all design cases were classified into the cases performed considerably better under the ABS or CMPR approaches in each climate zone based on the classification method developed in the present study (explained in Section 2.1).

2.5 Performance metrics

The performance path uses quantitative metrics to evaluate the energy consumption of the proposed building. The performance metrics used in the current study were determined on the basis of NBC (NRC 2015) Part 9.

The performance metric used for the CMPR approach was the *percentage-better-than-code* metric. As per NBC's (NRC 2015) Sentence 9.36.5.3.(2), a proposed house's annual energy use shall be less than or equal the reference house's

Table 3 Considered scenarios in simulating proposed houses. Note that the variable of *n* is replaced with the climate zone number (i.e. 4, 5, 6, 7A, 7B, and 8)

Scenario	Abbreviation	Description
1	CZn-Baseline	Archetypes were simulated in climate zone *n* with identical specifications.
2	CZn-ACH	Archetypes were simulated in climate zone *n* with identical specifications but various airtightness levels.
3	CZn-Wall	Archetypes were simulated in climate zone *n* with identical specifications but various wall assemblies.
4	CZn-Window	Archetypes were simulated in climate zone *n* with identical specifications but various window assemblies.

Table 4 Design specifications of proposed houses under the CZn-Baseline scenario

Category	Component/System	Specification
Baseload	Lighting and electrical appliances	19.5 kWh/day
	DHW load	190 L/day
Envelope	Airtightness	1.5 ACH @ 50 Pa
	Wall	RSI-value = 4.59 m^2·K/W
	Window	U-value = 1.08 W/(m^2·K), SHGC = 0.26
	Door	RSI-value = 0.71 m^2·K/W
	Exposed floor	RSI-value = 5.02 m^2·K/W
	Ceiling	RSI-value = 5.02 m^2·K/W
	Foundation walls (interior)	RSI-value = 2.98 m^2·K/W
	Foundation slab on grade	RSI-value = 1.96 m^2·K/W
HVAC/DHW	Heating	Electric baseboard
	DHW	Electric tank heater

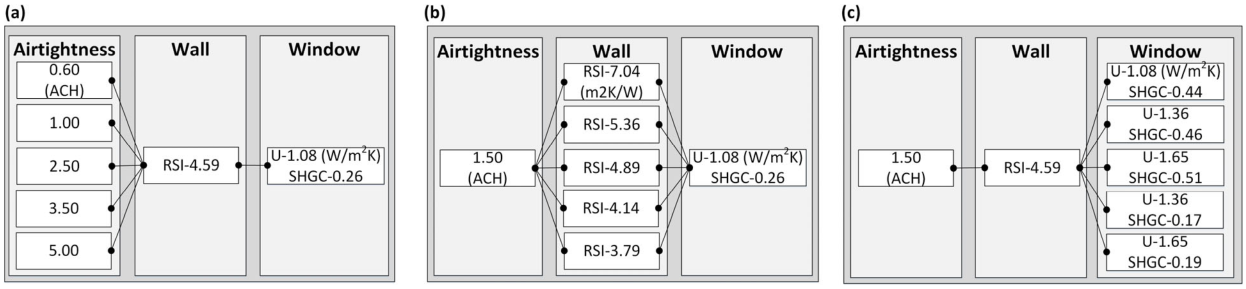

Fig. 3 Various envelope design options simulated: (a) altered airtightness (CZn-ACH), (b) altered wall assemblies (CZn-Wall), and (c) altered window assemblies (CZn-Window)

annual energy use. The annual energy use (E) shall be calculated according to NBC's (NRC 2015) Sentence 9.36.5.4.(1) using Eq. (1):

$$E = E_{\text{Heating}} + E_{\text{DHW}} + E_{\text{Ventilation}} + E_{\text{Cooling}} \quad (1)$$

where E_{Heating}, E_{DHW}, $E_{\text{Ventilation}}$, and E_{Cooling} are the annual energy used for space heating, domestic hot water, mechanical ventilation, and space cooling (where applicable), respectively.

The *percentage-better-than-code* (%) was obtained using Eq. (2):

$$\textit{percentage-better-than-code} = 100 \times \frac{E_{\text{Reference}} - E_{\text{Proposed}}}{E_{\text{Reference}}} \quad (2)$$

where $E_{\text{Reference}}$ is the annual energy use (kWh) of the reference house and E_{proposed} is the annual energy use (kWh) of the proposed house.

On the basis of NBC's (NRC 2015) calculation method for annual energy use, the *EUI* metric (kWh/m²) was used as the performance metric for the assessment of proposed houses' energy performance based on the ABS approach. A proposed house's *EUI* was calculated using Eq. (3):

$$EUI = \frac{E_{\text{Proposed}}}{A_{\text{floor}}} \quad (3)$$

where A_{floor} is the total heated floor area (m²). Note that the total heated floor area is calculated as the sum of the floor area of all conditioned spaces of a house regardless of their ceiling heights.

3 Results and discussion

This section presents the main findings of the simulation results for the four considered scenarios explained in Section 2.4 (see Table 3). While simulations of the current study covered the Canadian climate zones, the main findings of this research are expected to generally apply to heating-dominated climates.

3.1 Baseline

Figure 4 presents the distribution of *EUI* and *percentage-batter-than-code* of all the archetypes in each climate zone. The simulation results show that proposed houses generally had larger *EUI* and smaller *percentage-batter-than-code* in colder climate zones than that in milder climate zones.

The archetypes were then classified into the Archetypes-ABS and Archetypes-CMPR classes based on *EUI* and *percentage-batter-than-code* separately within each climate zone to study if the ABS and CMPR approaches delivered identical design outcomes, referring back to the first research question. For this purpose, archetypes simulated under the CZn-Baseline scenario were ranked separately within each

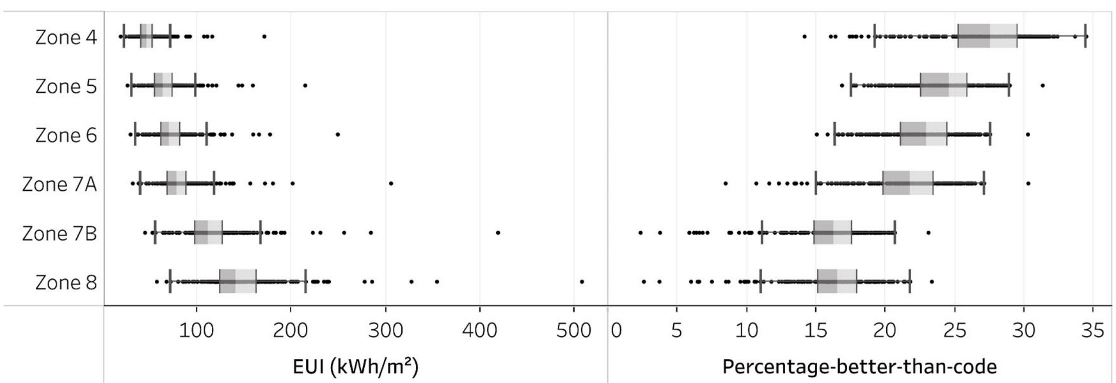

Fig. 4 Distribution of *EUI* and *percentage-batter-than-code* of all archetypes in each climate zone

climate zones. Ranks of archetypes were then averaged across all climate zones. Afterwards, the archetypes were reranked according to their mean ranks based on the *EUI* and *percentage-batter-than-code* metrics.

Note that this analysis included all archetypes even if they did not meet the NBC's requirements (i.e. a proposed house's energy use shall not exceed their reference houses' energy use). Figure 5 presents ranks of archetypes averaged across all climate zones. This figure shows that there were a large number of archetypes that performed differently under the ABS and CMPR approaches. The three classes of archetypes (explained in Section 2.1) presented in this figure indicates that there were some archetypes (i.e. Archetypes-ABS) that exhibited smaller *EUI* relative to their peer archetypes, but demonstrated only modest savings relative to the reference house when compared to other archetypes. There were also some other archetypes (i.e. Archetypes-CMPR) that performed noticeably better than their reference house when compared to other archetypes while also exhibiting larger *EUI*s. These observations indicate that the approach used in performance compliance affects design outcomes. Hence, it is of high importance to understand the outcomes from these two different approaches.

The annual energy use of the Archetypes-ABS and Archetypes-CMPR classes were compared to each other to characterize the energy efficiency outcomes of the ABS and CMPR approaches for the exploration of the second research

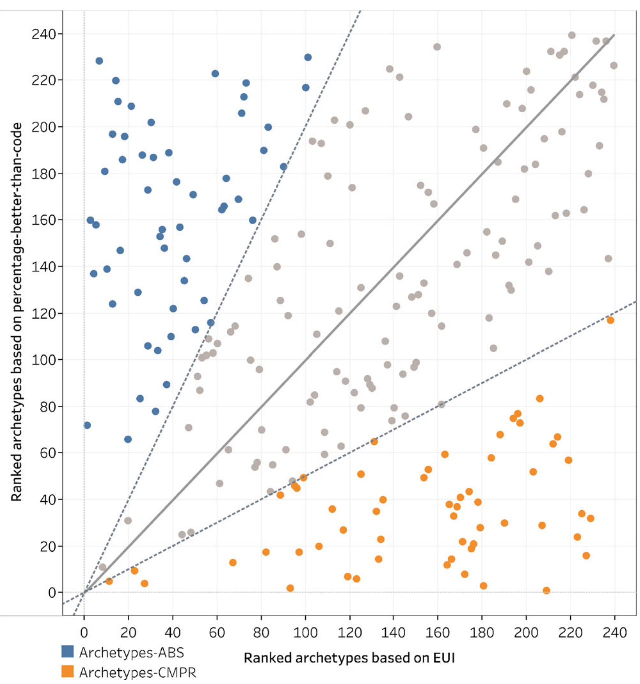

Fig. 5 Ranks of archetypes averaged across all climate zones under the CZn-Baseline scenario

question. Figure 6 presents the annual energy use distribution of the two classes in each climate zone. As expected, Archetypes-ABS exhibited lower *EUI*, while Archetypes-CMPR exhibited higher *percentage-better-than-code*. However, Archetypes-ABS consistently used less annual energy (GJ/year) than Archetypes-CMPR across all climate zones. This was true for houses built for the proposed design specification, and it was also true for houses meeting the reference house specification. While Archetypes-CMPR exhibited greater savings relative to the code reference house, their corresponding code reference house also exhibited more energy use than the code reference house for Archetypes-ABS.

This observation indicates that a proposed design's performance improvement relative to the reference house does not necessarily lead to lower energy use because the reference house benchmark also reflects the form of the proposed design. The CMPR approach may obscure the energy performance of a building in absolute terms. Hence, using *EUI*-based metrics may facilitate comparing the energy use of a building to its peer ones, leading to further transparency and simplicity. Mlecnik et al.'s (2010) study on the opportunities and barriers for energy labelling in Europe also proposed that using *EUI*-based metrics can expedite the adoption of energy labeling programs due to more transparency.

The design characteristics of the two classes of archetypes were then examined further to answer the third research question. Figure 7 summarizes the floor, wall, and window area characteristics of these archetypes. Archetypes-ABS and Archetypes-CMPR exhibited significant differences in three design characteristics: (1) wall area, (2) window area, and (3) gross wall to floor area ratio.

As the *EUI* metric is computed by dividing energy use by heated floor area, the authors anticipated that floor area would also be a significant determinant as to whether an archetype was classified as part of Archetypes-ABS or Archetypes-CMPR, similar to previous studies' findings (e.g. Charron 2018). However, Figure 7 shows that the floor area of the two sets of archetypes were similar. Both sets included large and small houses, and the median values in the two sets were nearly equal.

Figure 8 further explores the relationship between floor area and metrics of the ABS and CMPR approaches. The left hand graph plots the heated floor area of each archetype, ordered by its rank under the ABS approach. The right hand graph plots the same archetypes, ordered by their ranks under the CMPR approach. Neither the *EUI*-based ranks nor *percentage-better-than-code*-based ranks exhibited strong correlation to floor area (R^2 of 0.17 and 0.09, respectively), indicating that other design characteristics were likely more important in determining performance under the

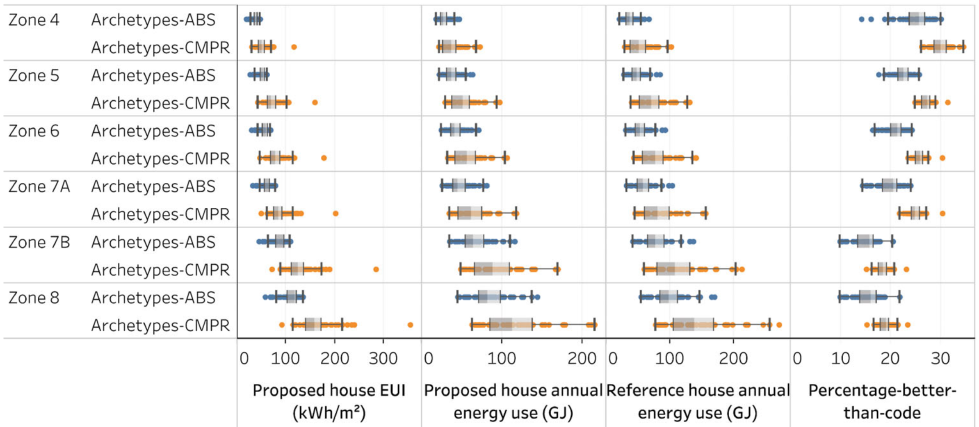

Fig. 6 Comparison of energy-related characteristics between Archetypes-ABS and Archetypes-CMPR in each climate zone

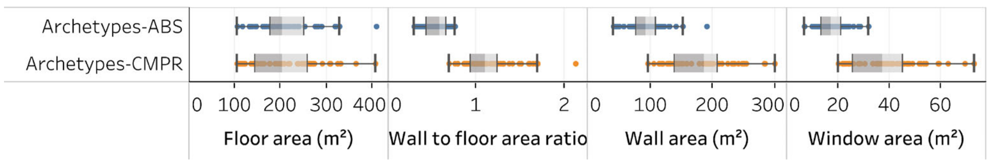

Fig. 7 Comparison of geometry-related characteristics between Archetypes-ABS and Archetypes-CMPR in all climate zones

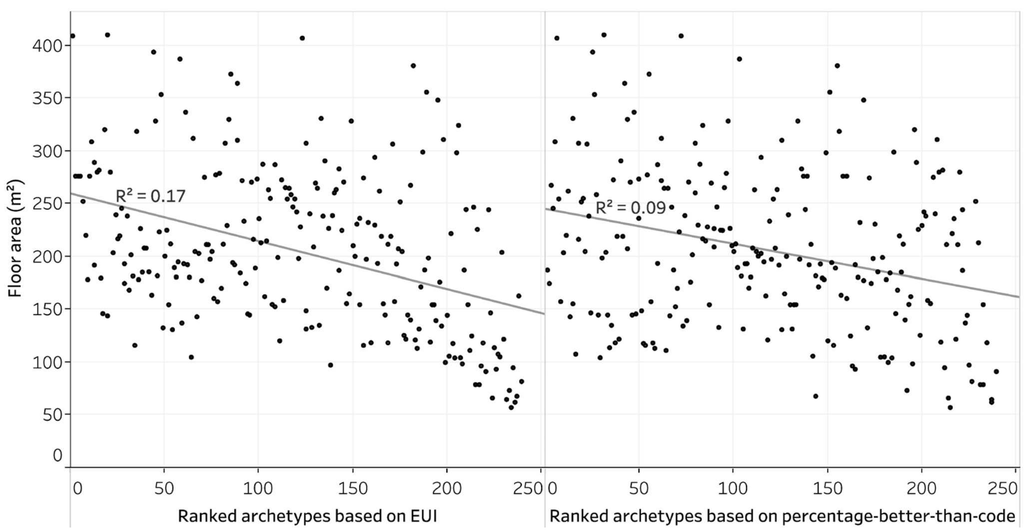

Fig. 8 Relationship between floor area and ranks of archetypes based on *EUI* and *percentage-better-than-code* in all the climate zones

ABS and CMPR approaches. While the trend does suggest that the best-ranked archetypes under the ABS approach are larger than the worst-ranked archetypes, the archetypes exhibited a nearly identical trend when ranked under the CMPR approach. These results suggest that the ABS approach did not provide strong incentive to design larger houses, and that any preference towards larger houses was likely no different than under the CMPR approach. While careful examination of Figure 8 determined that very small houses (< 100 m²) tended to perform poorly under the ABS approach, the same houses also performed poorly under the CMPR approach. While individual house designs may be favoured by either the ABS or CMPR approach, analysis across all 240 archetypes indicates that adopting the ABS approach instead of the CMPR approach did not significantly bias the code towards larger houses.

Figure 7 also compares the wall and window areas of the two sets of archetypes. It shows that Archetypes-CMPR generally exhibited greater wall and window areas than Archetypes-ABS. The ratio of gross wall area to floor area (also known as vertical surface area to floor area ratio (VFAR) in BC Housing's (2018) metrics research report) is sometimes used to express the "compactness" of a house design. In all but 3 cases (out of 58 Archetypes-CMPR), Archetypes-CMPR exhibited higher (or less-compact) ratios than those found in Archetypes-ABS (58 cases) in each climate zone. Higher ratios of Archetypes-CMPR than Archetype-ABS may lead to the impression that a proposed house with a large gross wall to floor area ratio (i.e. less compact design form) is better than a proposed house with a small gross wall to floor area ratio when a house designed under the CMPR approach. This trend is because when a proposed house has a larger gross wall to floor area ratio, the reference house will have a larger energy budget than when a proposed house has a smaller gross wall to floor area (Figure 9).

These findings indicate that the ABS approach encourages design of houses with smaller gross wall to floor area ratio (i.e. more compact form), and that such houses are likely to consume less energy than houses designs favoured by the CMPR approach. Similarly, Casals' (2006) analysis of building energy regulations in Europe and specifically the Spanish regulation proposal discussed that the variable reference building under the general option of the code proposal leads to less compact forms of buildings with higher energy use. Several previous studies (Depecker et al. 2001; Pachecoe et al. 2012; Hemsath and Alagheband Bandhosseini 2015) also highlighted the important role of compact design form on building energy use.

Figure 6 also shows that the interquartile range (IQR) of Archetypes-CMPR's *EUI* was larger than the IQR of Archetypes-ABS's *EUI*. Similarly, the IQRs of Archetypes-CMPR's gross wall to floor area ratio and wall and window area were larger than that of Archetypes-ABS. This comparison indicates the more diverse design outcomes of the CMPR approach relative to the ABS approach with respect to energy predictions and envelop design. As such, using the

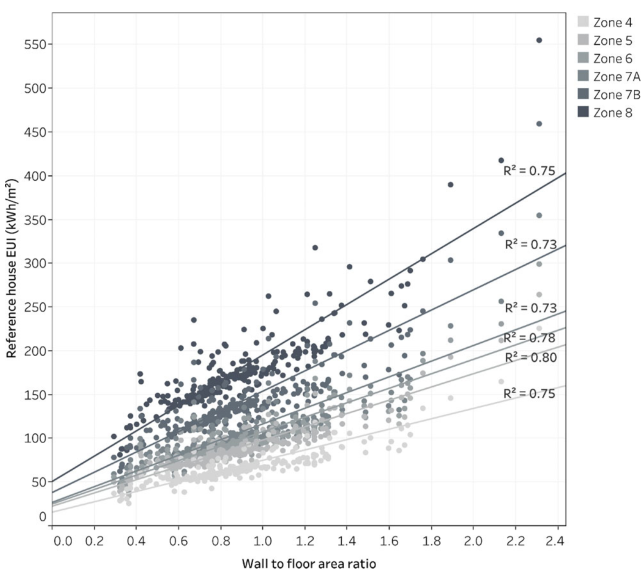

Fig. 9 Relationship between gross wall to heated floor area ratio and energy budget of the reference house of each archetype simulated under the CZn-Baseline scenario in each climate zone

CMPR approach in a code compliance process increases the uncertainty levels of a design outcome relative to the ABS approach. This uncertainty also makes it difficult to define consistent levels of saving percentages in energy initiatives adopting the CMPR approach. Pérez-Lombard et al.'s (2009) review of energy certification schemes also showed the discrepancy between labelling scales of various rating systems (BREEAM, Spanish CALENER, CEN, American LEED-NC) that use the CMPR approach.

Generally speaking, design outcomes of each approach revealed common physical characteristics in the current study. Olofsson et al.'s (2004) study also indicated that similar physical characteristics of their considered houses led to similar relative performance among them under various metrics. Table 5 presents a summary of the common characteristics of the Archetypes-ABS and Archetypes-CMPR classes observed in the current study.

As the BPS tool HOT2000 does not generate a model's three-dimensional geometry, the form of the archetypes was visually inspected using satellite, aerial, and street imagery. From this visual survey, representative illustrations of the archetypes were developed.

Figure 10 presents examples of eight archetypes: four from the archetypes that performed generally better under the ABS approach and four from the archetypes that performed generally better under the CMPR approach. As shown in Figure 10(a), common characteristics observed among the archetypes that performed better under the ABS approach included compact and cubic shapes and attached housing forms (duplexes, row houses and multi-family units). These design features help reduce the external envelope of houses, thereby minimizing heat loss. On the contrary, common characteristics among the archetypes that performed better under the CMPR approach included detached houses with articulated forms and high aspect ratios, and large external envelope surfaces including exposed floors (Figure 10(b)).

Under the CMPR approach, similarity between a proposed building and its equivalent reference building affords design flexibility to builders. However, the energy impacts of architectural design decisions are neglected by the CMPR approach, because the reference house form matches that of the proposed design (Arent et al. 2020). Moreover, a proposed building incorporating features known to increase energy use (e.g. exposed floors) are matched to a similar-shaped reference building, thereby increasing the reference building's energy budget and energy improvement of the proposed building relative to its reference building. Accordingly, the CMPR approach may encourage builders to incorporate such features into designs, whereas the ABS approach actively discourages the use of such features.

Table 5 Summary of comparing main characteristics of Archetypes-ABS and Archetypes-CMPR under the CZn-Baseline scenario

Characteristics of proposed houses	Class #1 (Archetypes-ABS)	Class #2 (Archetypes-CMPR)	Notes
Annual energy use	↓	↑	Archetypes-CMPR's *annual energy use* was 38%* larger than that of Archetypes-ABS.
Floor area	—	—	Both sets of archetypes exhibited similar floor area.
Gross wall to floor area ratio	↓	↑	Archetypes-CMPR's *gross wall to floor area ratio* was 87%* larger than that of Archetypes-ABS.
Wall area	↓	↑	Archetypes-CMPR's *wall area* was larger than that of Archetypes-ABS by a factor of 2.0**.
Window area	↓	↑	Archetypes-CMPR's *window area* was larger than that of Archetypes-ABS by a factor of 2.2**.
Variability of energy predictions and envelope design	↓	↑	• IQR of Archetypes-CMPR's *EUI* was 71% larger than that of Archetypes-ABS. • IQR of Archetypes-CMPR's *gross wall to floor area ratio* was 31% larger than that of Archetypes-ABS. • IQR of Archetypes-CMPR's *wall area* was larger than that of Archetypes-ABS by a factor of 2.0**. • IQR of Archetypes-CMPR's *window area* was larger than that of Archetypes-ABS by a factor of 2.6**.

* Percentage differences are the percentage deviation of the median of Archetypes-CMPR from the median of Archetypes-ABS averaged across all climate zones.

** Increase factors reflect the increase in the median of Archetypes-CMPR from the median of Archetypes-ABS averaged across all climate zones.

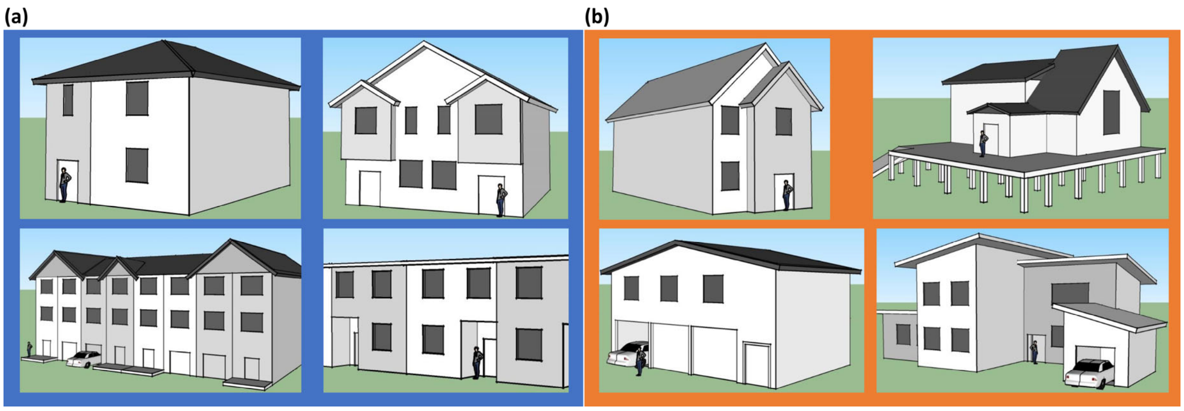

Fig. 10 Illustrative examples of: (a) archetypes performed generally better under the ABS approach, (b) archetypes performed generally better under the CMPR approach

3.2 Envelope parametric study

To compare the variations of envelope properties among the Archetypes-ABS and Archetypes-CMPR classes, airtightness and wall and window assemblies altered under the CZn-ACH, CZn-Wall, and CZn-Window scenarios (see Figure 3) in each climate zone. Under each scenario, archetypes with various envelope options were re-ranked based on *EUI* and *percentage-better-than-code* separately within each climate zone to identify the design cases fell into the Archetypes-ABS and Archetypes-CMPR classes.

Figure 11 presents the distribution of houses' ranks based on *EUI* and *percentage-better-than-code* under the CZn-ACH, CZn-Wall, and CZn-Window scenarios for all the climate zones. The simulation results show that houses with higher airtightness, improved wall insulation, or better windows obtained higher ranks based on both *EUI* and *percentage-better-than-code*, indicating the reduction in houses' *EUI* and the increase in *percentage-better-than-code*. However, from the least-efficient to the most-efficient options, the step improvement in the median rank of houses based on *percentage-better-than-code* was greater than that of the median rank of houses based on *EUI*.

All the houses were then classified based on *EUI* and *percentage-better-than-code* under the three scenarios in each climate zone to investigate the variations of envelope properties between the Archetypes-ABS and Archetypes-CMPR classes. Figure 12 presents similar trends of the distribution of the considered envelope options in the Archetypes-ABS and Archetypes-CMPR classes in all the climate zones. This figure shows that 61% of Archetypes-CMPR in average across all the climate zones featured the

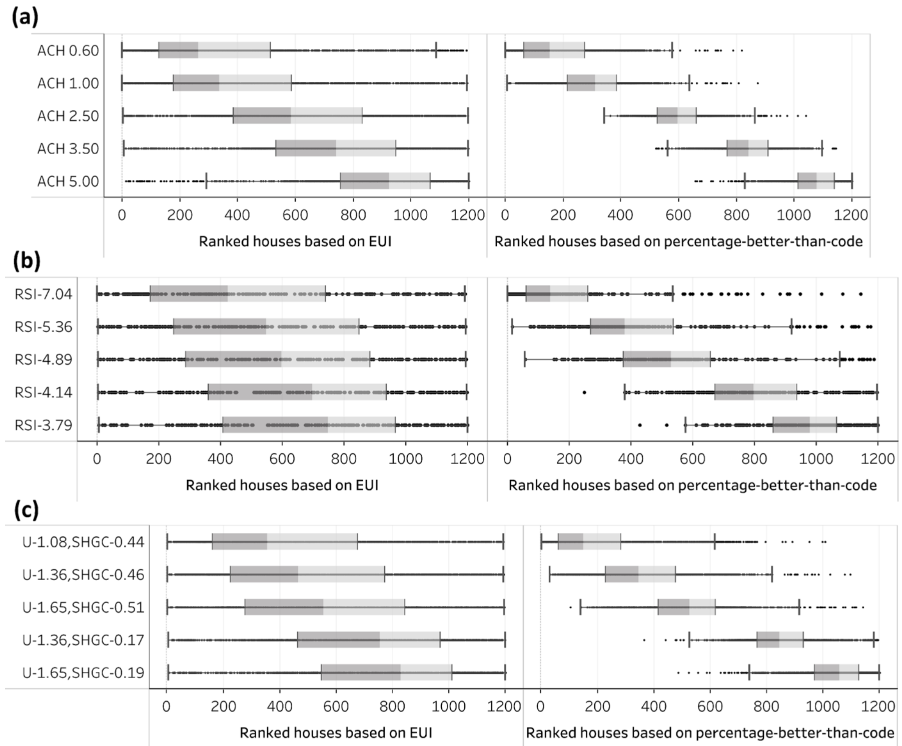

Fig. 11 Distribution of houses' ranks based on *EUI* and *percentage-better-than-code* under the: (a) CZn-ACH, (b) CZn-Wall, and (c) CZn-Window scenarios, for all climate zones

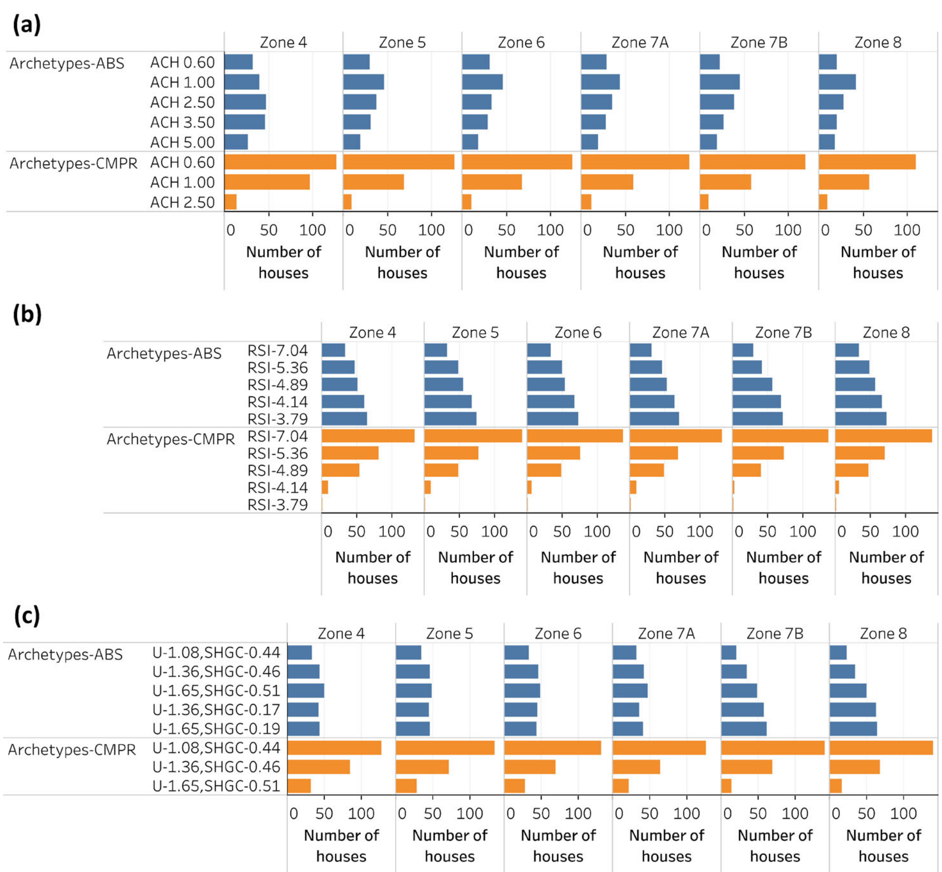

Fig. 12 Distribution of various options for airtightness and wall and window assemblies under the three scenarios: (a) CZn-ACH, (b) CZn-Wall, (c) CZn-Window in each climate zone

highest airtightness level (i.e. 0.6 ACH @ 50 Pa) while 17% of Archetypes-ABS featured the highest airtightness levels. The distribution of various wall assemblies shows that 51% and 12% of Archetypes-CMPR and Archetypes-ABS in average across all the climate zones, respectively, had the best insulated wall (i.e. RSI-7.04). Likewise, Figure 12 shows that 58% of Archetypes-CMPR had the highest performing window (i.e. U-1.08 with SHGC-0.44) among the considered window options, whereas 14% of Archetypes-ABS had this window type. In all the considered cases, a smaller number of Archetypes-ABS (relative to Archetypes-CMPR) had the highest performing envelope option among the considered options.

Additionally, for the examination of energy savings, incremental changes in *EUI* and *percentage-better-than-code* of each considered envelope option relative to the baselines (i.e. CZn-Baseline) were calculated for each archetype fell into the Archetypes-ABS and Archetypes-CMPR classes of the baselines in each climate zone. Figure 13 presents the simulation results for climate zone 7A under various alterations to envelope design. Similar trends were observed for all other climate zones, with the difference that alteration into the airtightness level or wall or window assemblies had a larger impact on the incremental change in *EUI* and *percentage-better-than-code* in colder climate zones than milder climate zones. This figure shows that as various envelope performance improved, the annual energy use of Archetypes-CMPR changed more than that of Archetypes-ABS.

The simulation results indicate that the compact form of Archetypes-ABS was a more influential factor than alterations into the Archetypes-ABS's envelope properties in achieving energy efficient houses when changing each parameter (i.e. airtightness, walls, and windows). Simply put, Archetypes-ABS were less sensitive to the considered envelope options than Archetypes-CMPR due to the fact that Archetypes-ABS had more compact forms. On the other hand, Archetypes-CMPR's energy performance was more sensitive to the considered alterations into envelope, indicating that the CMPR approach may incentivize builders for airtightness and envelope insulation more than the ABS approach.

These trends also indicate that the energy performance of Archetypes-CMPR improved more readily than that of Archetypes-ABS. Consequently, a code that adopts the CMPR approach as its performance path for compliance may encourage builders to construct houses with a less energy-efficient form. This is because building envelope improvements will deliver greater overall energy savings relative to the reference house in these homes. Casals' (2006) discussion of European building energy regulations also argued that with the CMPR approach, there would a high probability that a building with larger energy use gets the higher certification than its peer buildings with smaller energy use on identical sites. Similarly, several studies (Bourgeois 2018; Bleasby 2020; Meyer 2020) argued about these caveats of the CMPR approach as this approach neutralizes the impact of architectural features.

4 Limitations and future work

The necessity for further research is acknowledged as the present study has limitations as discussed in this section.

4.1 Study scope

This research did not aim at determining *EUI* targets for a code compliance, but rather performing a reliable comparison

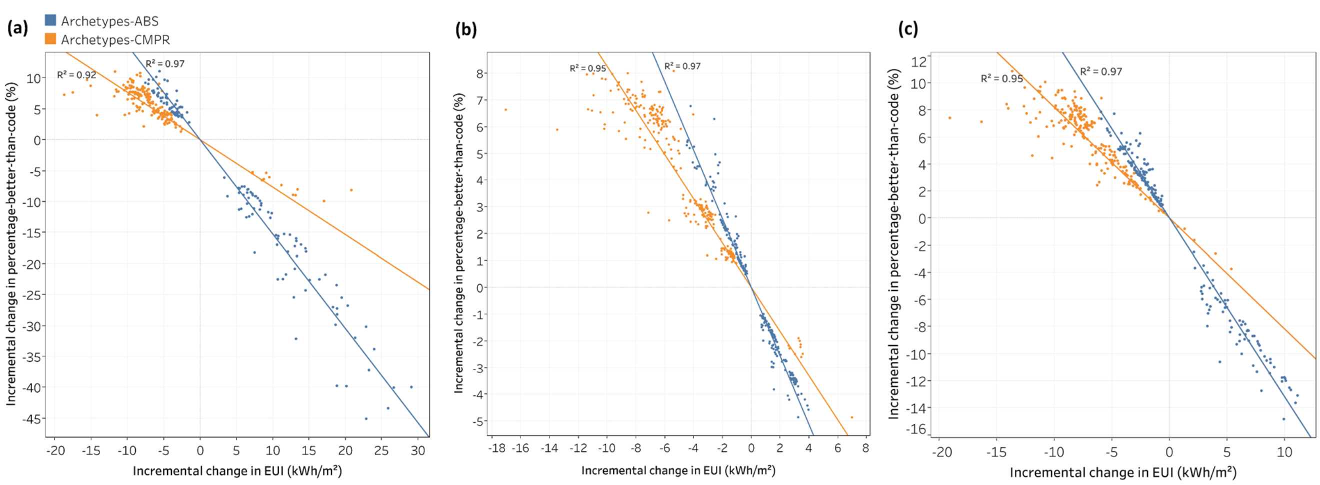

Fig. 13 Incremental change in *EUI* and *percentage-better-than-code* under the three scenarios: (a) CZ7A-ACH, (b) CZ7A-Wall, (c) CZ7A-Window in climate zone 7A

between the ABS and CMPR approaches. To this end, the current study included only regulated energy use. However, determination of absolute targets for the ABS approach may require considering unregulated energy use.

The present study also did not examine how design features of the archetypes that performed better under the ABS or CMPR approaches may reflect their architectural context. For instance, some archetypes used in this study include specialized design features to accommodate construction on narrow lots and on top of permafrost. These features are known to increase *EUI*. The suitability of the ABS approach in these contexts (and the existence of appropriate design solutions) warrants further research.

Likewise, it is well understood that the energy use estimation is highly dependent on the BPS tool used for building energy modeling. Thus, the establishment of robust requirements to test sensitivity of energy estimations to BPS tools is imperative when energy use in absolute terms is of interest.

The NRCan archetypes library used in the current study included only houses and low-rise residential buildings (i.e. NBC (NRC 2015) Part 9). However, there is a growing trend towards multi-unit mid/high-rise residential buildings (MURBs) across Canada (RDH Building Engineering Ltd. 2012). Hence, future work should include mid/high-rise MURBs. This topic must also be investigated for commercial buildings.

The visual inspection of the NRCan archetypes showed that there may a correlation between the compliance approach that a code adopts and forms of the houses comply with the code. Several previous studies attempted to provide guidelines for architects and engineers in designing energy-efficient building forms. For instance, Depecker et al. (2001) and Esteves et al. (2018) found that the more compact a building form is, the lower the energy use is in cold climates using various definitions for a form's compactness. Hemsath and Alagheband Bandhosseini (2015) also recommended that a building geometry should vary based on the climate. Future research on the impact of houses' forms on the energy use in absolute terms as well as relative to reference houses is necessary.

This study focused solely on heating-dominated climates. Future work might apply the archetype classification method to warmer regions where cooling is a major contributor to energy use.

Finally, this research analyzed the appropriateness of the code compliance approaches for houses from the energy perspective. However, reaching a consensus on which approach is best suited for a code compliance process necessitates studying other aspects as well, such as economic implications (e.g. affordability and equitability), to avoid potential unintended consequences. Such questions are deferred to code authorities.

4.2 Code scope

While the ABS approach offers advantages to building professionals (such as no requirement for modeling a reference building, easier submittal reviews), it imposes challenges on building energy codes, requiring further research.

The CMPR approach neutralizes the impacts of building operation and unregulated loads using identical assumptions in the proposed and reference buildings (Goldstein and Eley 2014; Bourgeois 2018). However, the ABS approach highlights the importance of accurate buildings' performance predictions, thereby requiring accurate building operation and unregulated loads assumptions (Rosenberg et al. 2015). For instance, verification of the Sweden BBR's specific purchased energy use intensity for compliance with the regulations is based on measurements, thus affected by actual building operation and unregulated loads (Allard et al. 2017). In this way, the ABS approach supports the predictive use cases of building energy modeling that involves closing the performance gap between actual and expected performance of a building as opposed to the standardized or representative use cases (Karpman and Rosenberg 2020).

Comparing a building's performance with its peer buildings' is imperative when absolute targets are taken into account. For instance, the median of energy use intensity of aggregated statistical data can be considered due to its less sensitivity to individual buildings at scale (Sharp 1996; Olofsson et al. 2004). However, a building's energy use is affected by various factors, such as time, climate, and buildings' types and configurations (e.g. height, density), operation and maintenance, and space utilizations (Goldstein and Eley 2014; Rosenberg et al. 2015).

Hence, collection and development of comprehensive databases of buildings' performance such as China's Quota Standard (Liu et al. 2019) and Energy Star Portfolio Manager (EPA 2020) considering various contextual information is a critical prerequisite for absolute targets. For instance, absolute targets can be defined for various building types and climate zones (e.g. Liu et al. 2019). Likewise, absolute targets can be normalized by various factors. For instance, IEA/IPEEC's (2015) framework uses temperature correction to consider varying seasonal impacts in each individual location, climate normalization to consider the impact of climates for comparing multiple locations, and time-based normalization to analyze energy use differentiation to a reference year. These types of normalization such as energy use per capita can also facilitate higher density development in the building stock through the consolidation of code specification for low density development.

Absolute targets based on floor area can be an indicator of buildings' energy performance improvement resulted from technical aspects such as better envelope insulation, window size, and airtightness. However, an energy use intensity metric based on floor area may also be affected by non-technical aspects (Fairey and Goldstein 2016). For instance, Urban Equation/EQ Building Performance's (2019) study on MURBs in Toronto revealed that the studied MURBs performed differently under the *EUI* metric and energy use per suite. As a residential building's floor area per capita increases, the building energy use per floor area decreases since baseloads in residential buildings do not increase proportionally to floor area (IEA/IPEEC 2015; Bourgeois 2018).

Baseloads assumptions in simulation also affect calculated *EUI*. For instance, the current study did not change baseloads proportionally to floor area as observed by previous studies (IEA/IPEEC 2015; Bourgeois 2018), rather it used the baseloads assumption extracted from the EGH program's database. However, using various baseloads assumptions in the simulated archetypes changes *EUI* of small houses more than that of large houses (Figure 14), suggesting further research on baseloads assumptions in simulating residential buildings.

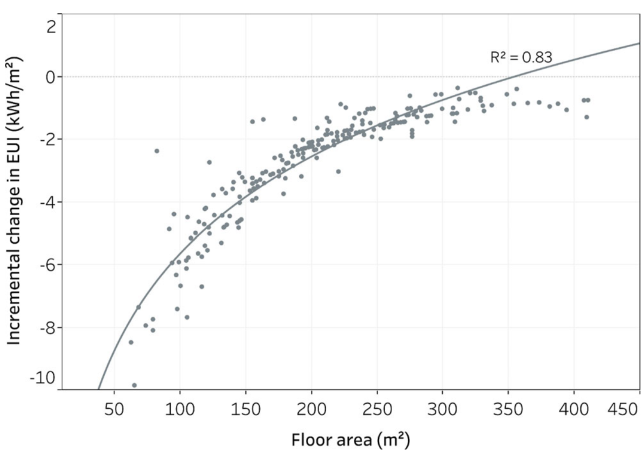

Fig. 14 Relationship between heated floor area and incremental change in *EUI* with more energy-conservative baseloads assumption relative to NBC's baseloads assumption in climate zone 7A. Note that this graph presents simulation results of two scenarios similar to the CZ7A-Baseline scenario except that baseloads were modified for two simulation runs. In the first run, baseloads of the archetypes were simulated in accordance with NBC (20.0 kWh/day). In the second run, baseloads of the archetypes were simulated based on a more energy-conservative assumption (16.9 kWh/day). Each dot in this graph represents each of the simulated archetypes

5 Conclusions

This research examined a statistically representative sample of contemporary Canadian housing to evaluate the energy performance of design outcomes of the ABS and CMPR approaches across a range of heating-dominated climates. The simulation results showed that compliance approaches are an important consideration for the performance path from the energy perspective.

The results indicated that the ABS approach may encourage design of houses with lower energy use and more compact form relative to the CMPR approach. The simulation results showed that the annual energy use of Archetypes-CMPR was 38% larger than that of Archetypes-ABS. The gross wall to floor area ratio of Archetypes-CMPR was 87% larger than Archetypes-ABS. Additionally, the results indicated the more diverse design outcomes of the CMPR approach compared to the ABS approach. The interquartile range of Archetypes-CMPR's *EUI* and gross wall to floor area ratio were 71% and 31% larger than that of Archetypes-ABS. These findings indicated that while the CMPR approach offers more flexibility to builders, the impact of optimal architectural form in the early design phase may not be captured using this approach.

The results of this research also showed that the compact form of the proposed houses under the ABS approach reduced their sensitivity to airtightness and envelope properties in comparison with the design outcomes of the CMPR approach. The simulation results of the envelope parametric study showed that 17%, 12%, and 14% of Archetypes-ABS had the highest airtightness level, best insulated wall, and highest performing window, respectively, among the considered envelope options. However, these values in the same orders were 61%, 51%, and 58% for Archetypes-CMPR. These findings indicated that code authorities opting for the ABS approach may find that builders have less incentive to invest in airtightness and insulation as they opt for more compact housing forms.

The simulation results of this research provided evidence for the better performance of the ABS approach relative to the CMPR approach from the energy perspective within the context of the Canadian housing stock. This study suggests that the adoption of the *EUI*-based ABS approach in the Canadian building codes would encourage builders to design and build houses with higher energy efficiency. The present study was performed for all the Canadian climate zones, however the main findings are expected to generally apply to heating-dominated climates.

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References

Allard I, Olofsson T, Nair G (2017). Energy performance indicators in the Swedish building procurement process. *Sustainability*, 9: 1877.

ANSI/ASHRAE (2014). ANSI/ASHRAE Standard 140-2014. Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ANSI/ASHRAE/IES (2016). ANSI/ASHRAE Standard 90.1-2016. Energy Standard for Buildings ecept Low-Rise Residential Buildings. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Arent J, Athalye R, Taylor S (2020). Clearing the path to ZNE with energy codes. *ASHRAE Transactions*, 126(2): 47–54.

Asaee R, Ferguson A (2018). Development of New Archetypes for Building Code Analysis—Part 1: New Housing. Ottawa, ON, Canada: Natural Resources Canada.

Asaee R, Ferguson A, Wills A (2019). Application of a housing technology assessment simulation platform in regulation R&D. In: Proceedings of the 16th Annual IBPSA International Conference, Rome, Italy.

ASHRAE/AIA/IES/USGBC/DOE (2018). Advanced Energy Design Guide for K-12 School Buildings. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE/AIA/IES/USGBC/DOE (2019). Advanced Energy Design Guide for Small to Medium Office Buildings: Achieving Zero Energy. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Attia S, Eleftheriou P, Xeni F, et al. (2017). Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy and Buildings*, 155: 439–458.

BC Housing (2018). Energy Step Code—Building Beyond the Standard: Metrics Research. British Columbia.

Berardi U (2017). A cross-country comparison of the building energy consumptions and their trends. *Resources, Conservation and Recycling*, 123: 230–241.

Bleasby J (2020). Energy efficiency advocates concerned about direction of 2020 NBC. Available at https://canada.constructconnect.com/dcn/news/projects/2020/11/energy-efficiency-advocates-concerned-about-direction-of-2020-nbc. Accessed 27 Jan 2021.

Bourgeois D (2018). Building Energy Performance Codes: An Assessment of International Performance. Quebec, Canada: RD2 Inc.

California Energy Commission (2019). Building Energy Efficiency Standards for Residential and Non-Residential Buildings: Title 24, Part 6, and Associated Administrative Regulations in Part 1. California Energy Commission.

Casals XG (2006). Analysis of building energy regulation and certification in Europe: Their role, limitations and differences. *Energy and Buildings*, 38: 381–392.

CCBFC (2021). 2020-02 Meeting of the Standing Committee on Energy Efficiency. Canadian Commission on Building and Fire Codes (CCBFC), National Research Council Canada.

CCBFC/NRC (2015). National Building Code of Canada. Ottawa, ON, Canada: National Research Council of Canada (NRC).

CCBFC/NRC (2017). National Energy Code of Canada for Buildings. Ottawa, ON, Canada: National Research Council of Canada (NRC).

Charron R (2018). A proposed alternative to the BC energy step code targets. In: Proceedings of the eSim 2018 Conference, Montréal, QC, Canada.

City of Toronto (2017). City of Toronto Zero Emissions Buildings Framework.

City of Toronto (2018). Energy Efficiency Report Submission & Modelling Guidelines for the Toronto Green Standard (TGS) Version 3. Environment and Energy Division & the City Planning Division, City of Toronto.

De Wilde P (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41: 40–49.

Depecker P, Menezo C, Virgone J, et al. (2001). Design of buildings shape and energetic consumption. *Building and Environment*, 36: 627–635.

Enker RA, Morrison GM (2020). The potential contribution of building codes to climate change response policies for the built environment. *Energy Efficiency*, 13: 789–807.

EPA (2020). ENERGY STAR. Available at https://www.energystar.gov/buildings. Accessed 28 June 2020.

Esteves A, Matias E, Mercado MV, et al. (2018). Building shape that promotes sustainable architecture. Evaluation of the indicative factors and its relation with the construction costs. *Architecture Research*, 8: 111–22.

Evans M, Roshchanka V, Graham P (2017). An international survey of building energy codes and their implementation. *Journal of Cleaner Production*, 158: 382–389.

Fairey P, Goldstein PB (2016). Metrics for energy efficient buildings: How do we measure efficiency? In: Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA, USA.

Galvin R (2010). Thermal upgrades of existing homes in Germany: The building code, subsidies, and economic efficiency. *Energy and Buildings*, 42: 834–844.

Goldstein DB, Eley C (2014). A classification of building energy performance indices. *Energy Efficiency*, 7: 353–375.

Haltrecht D, Fraser K (1997). Validation of HOT2000™ using HERS BESTEST. *Building Simulation*, 5: 63–70.

Hemsath TL, Alagheband Bandhosseini K (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy*, 76: 526–538.

Huang B, Mauerhofer V, Geng Y (2016). Analysis of existing building energy saving policies in Japan and China. *Journal of Cleaner Production*, 112: 1510–1518.

IEA (2021a). Buildings: A Source of Enormous Untapped Efficiency Potential. Available at https://www.iea.org/topics/buildings. Accessed 15 Sept 2021.

IEA (2021b). Tracking Buildings 2020. Available at https://www.iea.org/reports/tracking-buildings-2020. Accessed 15 Sept 2021.

IEA/IPEEC (2015). Building Energy Performance Metrics: Supporting Energy Efficiency Progress in Major Economies. International

Energy Agency and International Partnership for Energy Efficiency Cooperation.

Karpman M, Rosenberg M (2020). Quality Assurance and Quality Control of Building Energy Modelling for Program Administrators. CSA Group.

Liu S, Hinge A, Guo SY, et al. (2019). Building energy consumption quotas: A policy tool toward sufficiency? In: Proceedings of the ECEEE Summer Study.

Meyer C (2020). New building codes under review not tough enough on energy efficiency, report warns. Available at https://www.nationalobserver.com/2020/10/20/news/new-building-codes-under-review-not-tough-enough-energy-efficiency-report-warn. Accessed 31 Jan 2021.

Ministry of Municipal Affairs and Housing (2019). Ontario's Building Code. Available at https://www.ontario.ca/page/ontarios-building-code. Accessed 4 Jan 2021.

Mlecnik E, Visscher H, van Hal A (2010). Barriers and opportunities for labels for highly energy-efficient houses. *Energy Policy*, 38: 4592–4603.

NRCan (2017). HOT2XP. Natural Resources Canada (NRCan). Available at https://www.nrcan.gc.ca/energy/hot2xp/7445. Accessed 4 Jan 2021.

NRCan (2019a). Housing Technology Assessment Platform (HTAP). Natural Resources Canada (NRCan). Available at https://github.com/NRCan-IETS-CE-O-HBC/HTAP. Accessed 28 Aug 2020.

NRCan (2019b). HTAP-Archetypes. Natural Resources Canada (NRCan). Available at https://github.com/NRCan-IETS-CE-O-HBC/HTAP-archetypes. Accessed 28 Aug 2020.

NRCan (2020a). EnerGuide Energy Efficiency Home Evaluations. Natural Resources Canada (NRCan). Available at https://www.nrcan.gc.ca/energy-efficiency/energuide-canada/energuide-energy-efficiency-home-evaluations/20552. Accessed 4 Jan 2021.

NRCan (2020b). EnerGuide-Rated New Homes. Natural Resources Canada (NRCan). Available at https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-homes/buying-energy-efficient-new-home/energuide-rated-new-homes/20578. Accessed 4 Jan 2021.

NRCan (2020c). The Energy Code in Your Province or Territory. Natural Resources Canada (NRCan). Available at https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-buildings/energy-efficiency-new-buildings/canadas-national-energy-code/energy-code-your-province-territory/20677. Accessed 4 Jan 2021.

NRCan (2020d). Tools for Industry Professionals. Natural Resources Canada (NRCan). Available at https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-homes/professional-opportunities/tools-industry-professionals/20596. Accessed 4 Jan 2021.

Nejat P, Jomehzadeh F, Taheri MM, et al. (2015). A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). *Renewable and Sustainable Energy Reviews*, 43: 843–862.

Olofsson T, Meier A, Lamberts R (2004). Rating the energy performance of buildings. *The International Journal of Low Energy and Sustainable Buildings*, 3.

Pacheco R, Ordóñez J, Martínez G (2012). Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, 16: 3559–3573.

Parekh A (2005). Development of archetypes of building characteristics libraries for simplified energy use evaluation of houses. In: Proceedings of the 9th International IBPSA Conference, Montréal, QC, Canada.

Parekh A, Charron R, Poirier S, et al. (2018). Testing of HOT2000 version 11 in accordance with ASHRAE Standard 140-2014. In: Proceedings of the eSim 2018 Conference, Montréal, QC, Canada.

Pérez-Lombard L, Ortiz J, González R, et al. (2009). A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes. *Energy and Buildings*, 41: 272–278.

RDH Building Engineering Ltd. (2012). Energy consumption and conservation in mid- and high-rise residential buildings in British Columbia.

Rosenberg M, Hart R (2014). Roadmap toward a predictive performance-based commercial energy code. In: Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA, USA.

Rosenberg M, Hart R, Zhang J, et al. (2015). Roadmap for the Future of Commercial Energy Codes. Washington, USA: Pacific Northwest National Laboratory.

Schettler-Köhler HP, Ahlke I (2018). EPBD Implementation in Germany: Status in December 2016. Bonn, Germany: Federal Institute for Research on Building, Urban Affairs and Spatial Development.

Schwarz M, Nakhle C, Knoeri C (2020). Innovative designs of building energy codes for building decarbonization and their implementation challenges. *Journal of Cleaner Production*, 248: 119260.

Sharp T (1996). Energy Benchmarking in Commercial Office Buildings. In: Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings.

Tulsyan A, Dhaka S, Mathur J, et al. (2013). Potential of energy savings through implementation of Energy Conservation Building Code in Jaipur city, India. *Energy and Buildings*, 58: 123–130.

Urban Equation/EQ Building Performance (2019). Sidewalk Labs Toronto multi-unit residential buildings study: Energy use and the performance gap. Sidewalk Labs.

Van Dronkelaar C, Dowson M, Burman E, et al. (2016). Corrigendum: A review of the energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering*, 1: 17. doi: 10.3389/fmech.2015.00017.

Yu S, Eom J, Evans M, et al. (2014). A long-term, integrated impact assessment of alternative building energy code scenarios in China. *Energy Policy*, 67: 626–639.

Yu S, Tan Q, Evans M, et al. (2017). Improving building energy efficiency in India: State-level analysis of building energy efficiency policies. *Energy Policy*, 110: 331–341.