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On the use of the reference building approach in modern building energy codes

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ABSTRACT

For decarbonization of the building sector to happen at scale, net-zero energy levels of operational efficiency must be achieved. A global consensus is emerging around the Passive House energy performance level (15 kWh/m^2/a thermal energy demand) as “net-zero energy ready”. Given the imperative to rapidly transform buildings and shortcomings of the traditional prescriptive approach, a growing number of building energy regulations are adopting the performance-based or outcome-based approach, seeking to mandate net-zero energy performance with ambitious timelines. Some such regulations are based on the Reference Building Approach (RBA) where the energy performance of a building is assessed based on a hypothetical building of the same design but meeting a set of minimum prescriptive requirements. More commonly, performance targets are defined in absolute terms, based on energy intensity metrics. Although the European version of the RBA reconciles the absolute and relative performance targets through mandatory statistical performance baselines, the RBA in North America is used as an independent alternative to absolute energy use/demand intensity metrics (kWh/m^2/a). This paper examines the North American Reference Building Approach, focussing on its implementation in the British Columbia Energy Step Code as an instructive example. It is shown that the RBA has serious flaws. Most importantly, by creating a sliding scale, the RBA does not deliver net-zero energy performance, while incentivizing inefficient designs and poor energy modeling practices. Despite the regional focus of the data, the conclusions are applicable to the RBA in general. Based on the results, it is recommended that the use of the RBA in building energy codes and standards be discontinued.

1. Introduction

With buildings responsible for 35% of the final energy use and 38% of the energy-related greenhouse gas (GHG) emissions globally [1], a massive transformation of the building sector is necessary. It has long been recognized that high-performance buildings have benefits that go beyond energy savings, e.g. occupant health and comfort [2,3] and contribution to many of the UN Sustainable Development Goals [4]. Still, the COVID-19 pandemic [5] has brought the implications of inadequate ventilation, poor indoor air quality and housing inequity into the spotlight, enhancing the impetus to transform buildings. While the required transformation includes many aspects other than energy efficiency, including sustainability and resilience, most jurisdictions have chosen to address the operating energy efficiency first.

Energy efficiency is the “first fuel” [6] and is widely acknowledged to be a critical element of achieving carbon–neutral communities. Decarbonizing low-performing buildings requires an unrealistically large supply of renewable energy, with costly generation and transmission infrastructure to support buildings as well as other sectors such as transportation. Offsetting greater energy use by increasing the supply of renewable energy, onsite or offsite, has been recognized as a non-viable mitigation or adaptation strategy [7–9]. The need to maximize energy efficiency has been internationally recognized at least since 2008, when the International Energy Agency (IEA) recommended [10] Passive House [11] levels

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Abbreviations: BC, British Columbia; ERS, EnerGuide Rating System; ESC, Energy Step Code; EPBD, Energy Performance of Buildings Directive; IEA, International Energy Agency; RBA, reference building approach; ref, reference building; r, envelope area to heated volume ratio [1/m]; MEUI, mechanical energy use intensity (annual) [kWh/m^2/a]; TEDI, thermal energy demand intensity (annual) [kWh/m^2/a]; NZE-r, net-zero energy ready.

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of operating efficiency in building codes. This point has been recently emphasized in the IEA's "Net-zero by 2050" roadmap [9] and a follow-up article [12].

An increasing number of building codes and standards are being implemented to push for higher levels of energy efficiency. See reference [7] for a comprehensive review of the global trends towards net-zero energy buildings. A major shift in the approach to regulating the energy demands of buildings has been the transition from prescriptive to performance-based or outcome-based [13–15] regulation. See references [15,16] for discussion. In performance-based codes, two basic approaches are used, setting either absolute or relative energy performance targets. This paper examines the former, namely the Reference Building Approach (RBA), which is particularly popular in North America. In summary, the RBA compares the energy performance of a given building against a hypothetical building of the same design, satisfying a set of prescriptive requirements for the individual envelope components and energy systems.

In an industry that has undergone little change in recent decades, the continued use of past regulation practices is often the preferred or easier choice. For instance, despite the planned transition to outcome-based codes, both the British Columbia Energy Step Code [17] and the National Building Code of Canada [18] permit the Reference Building Approach for small residential buildings. A thorough understanding of the outcomes achieved using the RBA is therefore required and precipitated the research presented in this paper.

This paper begins with an overview of established targets for energy efficiency in the building sector and the regulatory trends that seek to achieve such targets. A brief discussion of the Reference Building Approach and its alternatives is then presented, followed by analysis of data from British Columbia, Canada. Modeling data from dozens of projects is analysed to assess the effectiveness of RBA in delivering high-efficiency buildings. Finally, the implications of relying on the RBA in efficiency policies are discussed.

The terminology adopted in this paper, specifically in Sections 4 and 5, is generally in line with Canada's EnerGuide Rating System [19] and the British Columbia Energy Step Code [17] and might have slight differences with other sources or regulatory contexts. The term "reference building" in particular, which is used in various codes and standards to define a baseline for energy performance, has different meanings in North American and European contexts. In this paper, the term Reference Building Approach signifies the North American approach. To avoid confusion, the term "representative building" is used to refer to the hypothetical building used in the European approach. The two approaches are discussed in detail in Section 4.

2. What level of efficiency is required?

Accepting efficiency as the first step, the level of energy efficiency required for net-zero energy and emissions performance of buildings must be established. The IEA identifies a 60% reduction in global building energy use intensity necessary to achieve commitments under the Paris Accord, despite developing nations expanding energy services within the buildings [8].

The United Nations Framework Guidelines for Energy Efficiency Standards in Buildings [20] (the "Guidelines"), adopted in 2017, are an example of a growing movement seeking to ensure nations adopt outcome-based codes, setting out a global framework for enhancing the operating energy efficiency of buildings. A recent update to the Guidelines identifies its purpose to provide a principles-based performance guidance for building energy standards that is outcome-based and is part of an integrated sustainable energy system [21]. Goal 4 of the revision to the Guidelines states:

> "The energy required by buildings can be reduced to a level that can be supplied largely, perhaps exclusively, by non-carbon-based energy [...] **Limiting building heating and cooling requirements to 15 kWh/m^2/a in new buildings** and to 25 kWh/m^2/a for retrofits (final energy in conditioned space) each reduces energy needs sufficiently to permit renewable energy or zero carbon sources to meet most or all of the remaining space conditioning energy requirements. [...] Over time with improvements in technology and materials and with enhanced connections to the built environment, these targets could be improved further." [22] (emphasis added)

The Guidelines echo the conclusion of a 2008 report by the IEA [10] that at costs equal or close to those of conventional buildings, it is possible with existing technology to transform buildings to align with the highest standards of health, comfort, well-being and sustainability, including improved energy efficiency and reduced GHG emissions [22].

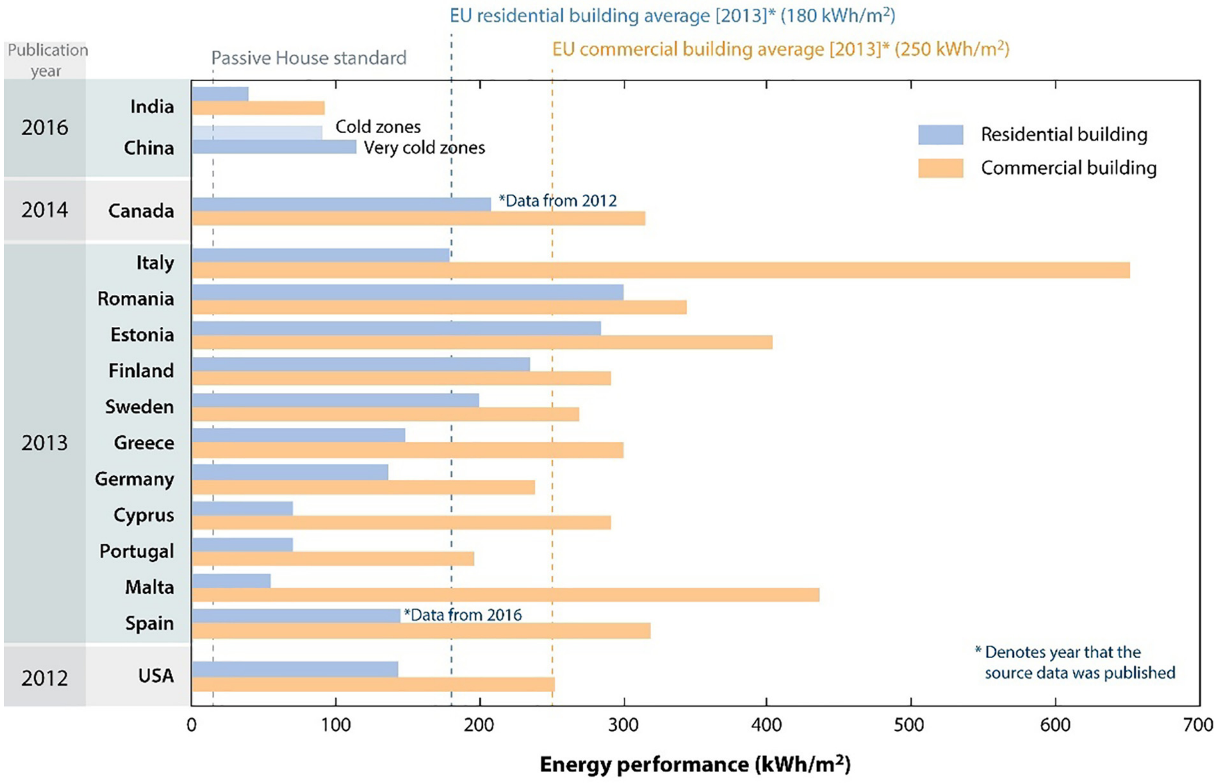
By incorporating the Passive House performance targets as a starting point to improve upon, the Guidelines are reflecting a growing number of national, regional and local initiatives mandating improvements of 60–80% in the efficiency of building stocks and/or setting performance targets for buildings. While establishing a universal energy demand target for all building types in all climates may not be realistic, the 15 kWh/m^2/a limit for space heating and cooling in new construction provides a solid benchmark. The feasibility of this performance level has been demonstrated for more than three decades, virtually across the world. Reference [7] provides a recent review and several examples.

Within the efficiency framework, the emphasis is first on the building envelope, and then on the mechanical systems. This "envelope first" approach has been recognized as the most effective and long-lasting way to improve the energy performance of buildings [23]. One reason for the central importance of the envelope first approach is that the building envelope should last the entire life of the building, while mechanical systems require replacement and can be more readily upgraded as better technologies become available. Of course, as the building fabric efficiency improves, mechanical energy use and unregulated plug and process loads represent an increasing proportion of total building energy use of up to 75% in commercial buildings [24] and must also be addressed.

3. Current regulatory trends

Decades of voluntary efficiency programs and other half-measures have not delivered the necessary transformation of buildings. In some cases, rating programs have produced a massive body of low-performing buildings, labelled "green". Fig. 1 [7] provides an overview of the energy performance of buildings globally and where different national building stocks are with respect to the established 15 kWh/m^2/a target. Given the enormity of the task at hand, the need for the development, implementation and enforcement of rigorous, stringent codes and standards to mandate and achieve maximum energy efficiency in new construction is incontrovertible.

Historically, building regulations took a prescriptive approach, setting minimum requirements for the specification of various building components, e.g. the R-value of envelope assemblies or the efficiency of air conditioning equipment. Recently, there has been a shift toward performance-based regulations, where the operation of the building as a whole system is regulated and requirements for the overall energy performance of the building



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Annu. Rev. Environ. Resour. 45:227–69

Fig. 1. Annual energy use intensity of residential and commercial buildings in various regions, reproduced from [7].

are set out. While performance-based regulations usually do not specify minimum requirements for individual components, some regulations, e.g. [11,25], use a combined approach, where performance criteria must be met while satisfying certain prescriptive requirements for individual components.

The UN Framework Guidelines [20] reflect a pattern among progressive building energy regulations seeking to achieve specific, measurable outcomes. A well-known example is the approach taken by the European Union in the Energy Performance of Buildings Directive [26]. Starting in 2002, the EU nations were mandated to establish energy performance requirements for new buildings, with a clear focus on outcomes [27]. Another early example of work advancing the concept of outcome-based codes can be found in reference [28].

Despite the endemic "performance gap" [29], namely the different between the predicted and operational energy use of a building, design-stage energy simulations can accurately predict the actual energy performance of buildings. Assessments of buildings built to the Passive House Standard [30–33] demonstrate this reality. Therefore, in addition to a general transition toward building regulations that deliver high-performance outcomes, there are also calls for project teams to be responsible for the in operational performance of their projects, e.g. the *Energiesprong* retrofit program in the Netherlands [34,35].

Despite an early start in Europe, the largest number of high-performance buildings are being delivered in China. Highly efficient buildings were first raised as a national goal in 2017 when performance targets approximating Passive House performance were set [36]. By October 2019, seven million square metres of ultra-low-energy buildings had been completed in China [37] and retrofits at a vast scale were planned.

A 2015 paper reviewing building codes in the USA, Europe & China [38] observes that [at the time] US building codes "do not regulate actual energy use during building operation" but focus on building design specification which can vary significantly from actual performance. It is further noted in reference [38] that US codes do not regulate significant portions of building energy demand such as process loads and plug loads. The paper [38] reports a growing level of advocacy for outcome-based codes, noting such codes are envisioned to provide a flexible pathway to realizing energy savings through innovative buildings design and technology solutions.

Canada provides a useful, and not atypical, example of a nation with building codes in transition. As the case studies presented in this paper are Canadian projects, the regulatory context merits a more detailed explanation. In the 2016 Pan-Canadian Framework on Clean Growth and Climate Change [39], the federal and provincial governments committed to a net-zero energy ready (NZE-r) model national building code by 2030. In 2017, Canada's energy ministers signed Build Smart – Canada's Buildings Strategy [40], mapping the path to the transformation of Canada's buildings to deliver the results described in the Pan-Canadian Framework and meet Canada's international commitments under the Paris Accord. The climate plan for the Province of British Columbia, CleanBC [41], reflects the national plan in terms of a provincial target of 80% improvement in building energy efficiency by 2032. In 2017, the Province of British Columbia adopted the Energy Step Code (ESC) [17] as a provincial standard which was then implemented as a compliance option in the British Columbia Building Code 2018 [42].

The evolution of the Energy Step Code in British Columbia, particularly the extension of the RBA as an alternative compliance pathway, provides an instructive example for policymakers. During development in 2016 and 2017, the ESC was considered an ambitious, leading performance-based code. By the time of its roll-out in 2018, while there was acknowledgement of certain shortcomings, it was celebrated as a remarkable start. As ESC was implemented, resistance to the implications of meeting the requirements, specifically the envelope performance targets, grew. In response to this resistance, the ESC was watered down rather than shored up. For example, the RBA was added for small buildings, not for specific archetypes or climate zones but across the board , even for archetypes and climate zones where no difficulty in meeting the original performance targets was reported. A similar pattern has emerged in the development of Canada's *National Model Building Code*, which is set to adopt the RBA [43,44]. Various stakeholders, especially municipalities, are becoming increasingly aware of the shortcomings of the RBA [45,46]. Recently, a subcommittee of the Energy Step Code Council resolved that the ESC, as currently enacted, does not achieve the stated goals of the Energy Step Code or CleanBC.

4. The reference building approach

4.1. Absolute vs relative performance targets

There are two common approaches to defining performance targets in building energy codes and standards. In the first approach, *absolute* performance targets are set based on the energy use (or demand) intensity metrics, i.e. the annual energy use (demand) per unit floor area (kWh/m^2/a). Energy intensity metrics may include only active space heating and/or cooling, e.g. thermal energy demand intensity or TEDI in the British Columbia Energy Step Code [42], or total space heating, water heating, space cooling and ventilation loads, e.g., mechanical energy use intensity or MEUI [42], or the total building energy uses, including plug and process loads, e.g. total energy use intensity or TEUI [42]. The metrics may also be calculated based on different floor areas, e.g. the *conditioned* floor area [42] or the *treated* (useful) floor area which *excludes* some conditioned areas [11]. Regardless of such differences in definition, the absolute performance targets all define measurable limits for the energy performance of a building. This approach has been successfully applied to a wide range of building archetypes in various climate zones, e.g. [47].

A prime example of performance-based regulations relying exclusively on absolute performance targets is the Passive House Standard [11]. As mentioned above, the EU requires outcomes-based regulations for all buildings in the member-nations [26], e.g. the national building codes of France (*Réglementation Thermique*) [48] and Germany (*Energieeinspaarverordnung*, EnEV) [49]. The Capital Region of Brussels essentially integrated the Passive House Standard into their building code in 2015 [50]. In Canada, the cities of Vancouver [51] and Toronto [52] both use EUI targets similar to the Passive House Standard in their zero-emission buildings plans. New Zealand's upcoming building code is heading in the same direction.

In the second approach, energy performance targets are defined with respect to a "reference" or "notional" building as baseline, in terms of relative improvements ("percentage better") than that baseline. The reference building (also known as notional building) is a *hypothetical building* of the same design as the building of interest, with envelope assemblies and energy systems that meet a set of minimum prescriptive requirements. The reference building approach (RBA) is currently used in ASHRAE 90.1 and 90.2 standards [53,54], and the building codes of Australia [55], California [56] and British Columbia [42]. In some cases, e.g. the British Columbia Energy Step Code (ESC), the relative targets based on the reference building are allowed as an alternative to the absolute energy use intensity targets. The RBA is also used in various voluntary building rating systems such as LEED in the USA and Canada [57], Green Star in New Zealand and Australia [58], ENERGY STAR in Canada [59], and the Home Energy Rating System [60]. New Zealand's building energy modeling standards [61,62] use the reference building approach.

It must be noted that the EU Energy Performance of Buildings Directive (EPBD) [26] also uses the term "reference building", but in a different sense. The EU reference building is a *statistical representative* of "the typical and average building stock in a member state". The EU reference buildings are therefore meant to represent the average existing building stock and used to establish baseline performance outcomes to be exceeded in retrofits or new construction. Notably, this approach creates a *universal* baseline for all buildings of the same archetype. Such representative baselines for existing buildings are currently used in the national implementations of the EPBD in Italy and Spain [63]. Several recent studies have examined this approach and proposed alternative methodologies for the derivation of representative buildings for various archetypes [64–66].

By definition, and as will be shown in Section 5, the reference building approach (RBA) creates a different performance baseline *for each single building*, even within the same archetype. This is the main different between the reference and representative buildings.

In North America, the RBA seems to have been popularized by the adoption of ASHRAE 90 standards [67]. Starting in 1975, motivated by the 1973 oil embargo. ASHRAE 90 set out minimum prescriptive guidance for new buildings. By the 1990 s, ASHRAE 90 standards became the baseline standard for energy efficiency in North America. In 2004, a "Performance Rating Method" was added to Standard 90.1 (for small residential buildings), providing a means of rating the energy efficiency of design options and an option under the US Green Building Council's LEED rating system [57].

Recent developments in various jurisdictions indicate continued, and in some cases emerging, use of the RBA despite growing concern about its ineffectiveness, e.g. the Energy Step Code in British Columbia [42], and the National Building Code of Canada [18] and the UK's Future Homes Standard [68]. The development of relative performance targets based on the RBA seems to have been driven also by policy objectives articulated in relative terms (e.g. 80% efficiency gain by 2032 [41]). Lack of historical data on the energy performance of the building stock and rigorous methodologies such as those used in the EPBD to establish reliable performance baselines seem to have helped the proliferation of relative performance targets in North America [69].

Although the RBA and its effectiveness in driving energy efficiency in the building sector have rarely been systematically studied, the literature does offer evidence of problems with this approach. For instance, the use of the RBA has been identified as a major contributor to the so-called performance gap [24,29,70], i.e. buildings not performing upon occupancy as well as predicted during design [29,71,72]. A recent report for the City of Toronto [52] found that for buildings permitted under the RBA, there was little correlation between the performance requirements of the energy standard the building was subject t o and the amount of energy it was designed to consume. A study of buildings in Vancouver [73] showed no correlation between building age and actual energy performance despite increasing code requirements over time. A report comparing different code systems [24] found that LEED certified buildings modelled using the RBA used even more energy than predicted for the code baseline. An examination of the performance of green certified projects in New Zealand found similar shortcomings [74]. A critique of the UK's current

RBA-based regulations can be found in [75]. Recommendations for absolute performance targets to replace relative performance improvements are presented in [76]. Discussions within the practitioners frequently highlight the issues. See for instance the recent article in an industry publication [77] where practitioners' preference for absolute metrics has been quoted.

4.2. Energy Step Code and the reference building approach

The British Columbia Energy Step Code (ESC) is the performance-based compliance pathway in the British Columbia Building Code [42], intended to progressively enhance energy efficiency in new construction up to NZE-r levels by 2032.

For small residential buildings no more than 600 m^2 in floor area and four storeys in height, the so-called "Part 9" buildings, performance targets are specified at five levels ("Steps"), with the highest performance level, Step 5, meant to be NZE-r. Each Step is defined in terms of thresholds for the tested air leakage rate from the building as well as thermal energy demand intensity (TEDI), which characterizes thermal performance (heat loss) of the envelope, and *mechanical energy use intensity* (MEUI), which characterizes the energy use of mechanical systems (space heating and cooling, ventilation, domestic water heating). See Equations (1) and (2).

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

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

In these equations, Q_{aux} is the annual "auxiliary" (active) heating demand [kWh/a], defined as the total (gross) space heat loss from the building envelope offset by the usable internal and solar heat gains; A is the conditioned floor area [m^2]; E_{tot} is the total annual energy use [kWh/a]; and E_{plug} is the annual plug (base) load [kWh/a].

The air leakage rate is determined based on blower-door tests, while MEUI and TEDI are calculated based on building energy simulations. The airtightness testing and energy modeling requirements are detailed in reference [42]. Details about post-processing the modeling results and calculating the ESC metrics can be found in reference [78]. To demonstrate compliance with ESC, small residential buildings are typically modeled using HOT2000 [79], following the EnerGuide Rating System (ERS) [19].

In addition to absolute performance targets, ESC contains alternative performance targets based on the RBA. The British Columbia Building Code 2018 [42] contained relative performance targets for building systems, based on the EnerGuide rating [19] of the house, as an alternative to the absolute MEUI targets. For instance, a house with more than 210 m^2 of conditioned space in Climate Zone 4 can achieve Step 2 with an EnerGuide rating of at least 10% better than the Reference House, instead of MEUI $\leq$ 65 kWh/m^2/a. In December 2019 relative performance targets for the thermal performance of the envelope were introduced as an alternative compliance pathway to the absolute TEDI targets. For instance, a house in Climate Zone 4 can achieve Step 2 with a thermal performance at least 5% better than the Reference House, instead of TEDI $\leq$ 35 kWh/m^2/a. Table 1 below summaries the performance targets of the BC ESC for small residential buildings Climate Zone 4 [42]. The absolute targets are less stringent for other climate zones, while the relative targets are the same.

Although RBA was permitted in ESC in calculating MEUI from the outset, the presence of absolute performance targets for the building envelope (TEDI) ensured a certain rigour; meeting the absolute TED target was, in most cases, more challenging that meeting the relative EnerGuide rating target. Nevertheless, with the addition of relative envelope performance targets as an alternative to the absolute TEDI targets, ESC for Part 9 buildings has adopted a full-on RBA.

5. The problem with the reference building approach

This section evaluates the performance outcomes achieved when using the RBA through several case studies, presented in two parts. In the first part, an analysis of the ESC's relative performance targets is presented, based on data from first 125 houses built under the ESC in Richmond, British Columbia. The second part examines the effects of some design parameters on the energy performance of buildings under ESC and how those parameters can be manipulated to achieve the relative performance targets.

5.1. The sliding scale: A different performance target for every building

As mentioned in Section 3, the ERS Reference House is a hypothetical building of the same design as the building of interest, with envelope assemblies and energy systems that meet a set of prescriptive minimum requirements. See references [19,42] for more details. Importantly, the reference building changes with the shape and size of the building of interest. Therefore, relative performance targets with respective to the ERS Reference House can translate to different absolute performance targets *for every single building.*

Fig. 2 shows the distribution of the Reference House TEDIs ($TEDI_{ref}$) of the first 125 single- and two-family dwellings built to the Energy Step Code in Richmond, BC. Even for the relatively small sample of N = 125, the wide range of $TEDI_{ref}$ is striking. Accordingly, a certain relative improvement in the performance of the building envelope could translates to significantly different results in terms of energy demand intensity (kWh/m^2/a). Alternatively, achieving the established thermal energy demand that enables net-zero energy operation of the building, namely 15 kWh/m^2/a (see Section 2), requires different relative improvements in the thermal performance of the building envelope – depending on $TEDI_{ref}$. For example, using the RBA, the 125 projects discussed here would comply with Step 5 with TEDIs ranging from 17.5 kWh/m^2/a to 37.5 kWh/m^2/a. Given the endemic performance gap, the actual

Table 1
Energy performance targets of the British Columbia Energy Step Code – Small residential buildings in Climate Zone 4 (HDD < 3000) [42].

Step	Envelope		Equipment and systems	
	TEDI [kWh/m^2/a]	Better Than Reference House [%]	MEUI* [kWh/m^2/a]	Better Than Reference House [%]
1	N/A	0	N/A	0
2	35	5	65	10
3	30	10	55	20
4	20	20	45	40
5	15	50	30	N/A

*These MEUI targets are only for houses with more than 210 m^2 conditioned floor area more than 50% of which is mechanically cooled. See reference [42] for the full list of the MEUI targets.

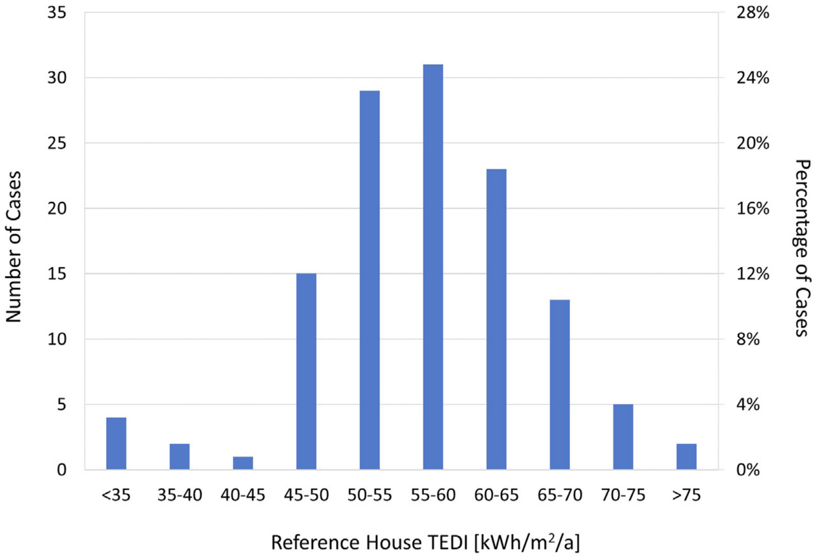

Fig. 2. Distribution of the Reference House TEDI based on energy models of 125 single- and two-family dwellings built under the Energy Step Code in Richmond, British Columbia.

building performance is likely even more varied. The “sliding scale“ created by the RBA leads to another difficulty: it is impossible to come up with the “”right” relative performance targets that delivers NZE-r performance (TEDI = 15 kWh/m^2/a).

5.2. Watered-down targets

Even if the fundamentally problematic aspects of the RBA are set aside, the specific relative performance targets of the BC ESC are significantly more lenient that the corresponding absolute performance targets. See Table 1, and Fig. 3 where the absolute and relative TEDI targets of the BC ESC are compared. In order to enable comparison, the absolute TEDI targets were translated into relative targets, using the data shown in Fig. 2. The average of the TEDI$_{ref}$ of those 125 cases was compared to the absolute performance target of each Step to calculate a corresponding relative improvement. For instance, the 40% improvement under the absolute target of Step 2 (the blue bar) was obtained by comparing the corresponding TEDI target (35 kWh/m^2/a) with the average TEDI$_{ref}$ (58 kWh/m^2/a).

As mentioned earlier, the sliding scale created by the RBA means a revised set of relative performance targets, e.g. 30% at Step 1, 40% at Step 2, etc., is unlikely to solve the problem. As the dataset expands (i.e. a wider variety of shapes, sizes and orientations is included), the absolute targets would translate to a different “equivalent” relative performance target, depending on the aver-

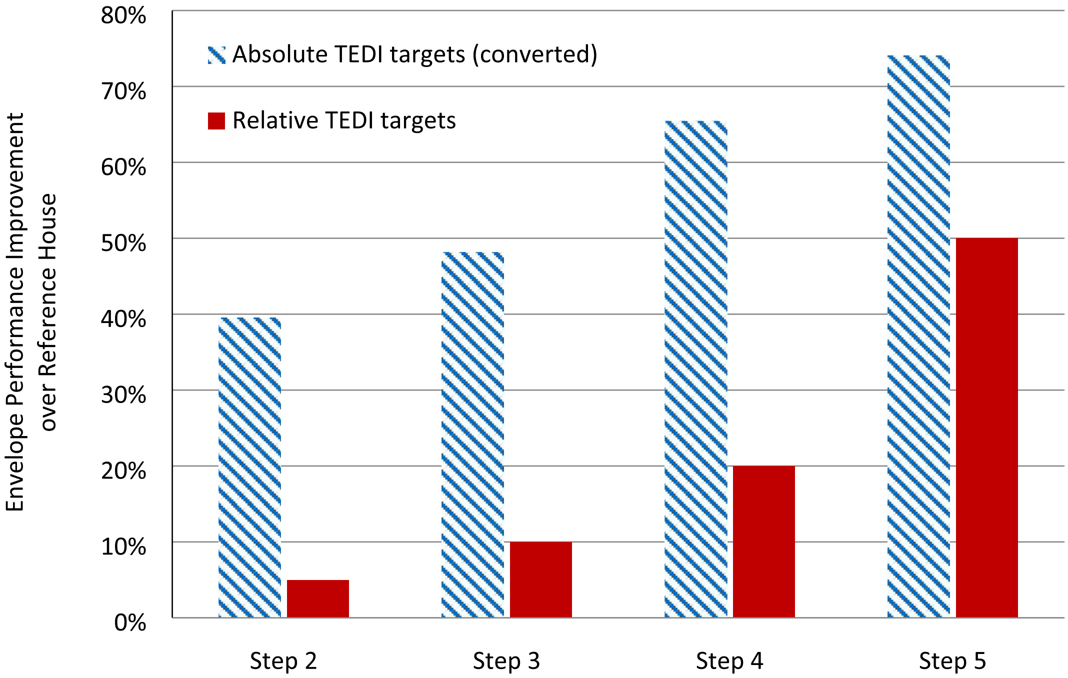

Fig. 3. Improvement of the building envelope performance over Reference House (prescriptive baseline) based on the absolute and relative targets of Energy Step Code. Absolute targets were converted to relative improvements based on the City of Richmond data.

age reference building TEDI. A main difficulty of using absolute and relative performance metrics as "interchangeable" is to come up with internally consistent targets. See reference [45] for further discussion and the policy implications.

Finally, it must be noted that, as shown in reference [80], given the uncertainties of building energy simulation, relative targets of 5% and 10% are too small to be meaningfully evaluated using the available data, methodologies and simulation tools.

5.3. Disregard for efficient forms

The shape or form of the building is a crucial determinant of the energy performance, especially in small residential buildings. Fig. 4 illustrates four sample plans, all having the same floor area but different forms. The square, the most compact form, is most efficient because it entails the smallest envelope area. This square house would be very unusual in the modern Canadian housing market; it is more typical of houses built before 1950. Highly efficient buildings tend to have a footprint that is close to case *b*. Inefficient forms with lots of indentation in the envelope (cases *c*,*d*) are seen across North America. The articulation in the exterior walls in Fig. 4 is exaggerated for illustration purposes, but the relative area to volume ratios are not exaggerated from what is common because the vertical dimension offers additional opportunities for inefficient design with complex roofs, foundations, garages, offset floor plans and other features.

To demonstrate the impact of form factor, the energy performance of four sample cases was modeled using HOT2000 [78] and following the EnerGuide Rating System [79]. The main formal features of the four cases are reported in Table 2.

The building form is usually characterized in terms of the ratio between the livable space (floor area or volume) to the exposed envelope area, i.e. the area through which heat exchange with the outdoors takes place. Here, area to volume ratio (*r*) is defined as the ratio between the exterior surface area of the envelope [m^2] and the heated volume [m^3] of the house. Identical or similar metrics are sometimes referred to as the "form factor" or the "compactness ratio."

In Fig. 5, the respective reference building TEDI ($TEDI_{ref}$) as well as the "50% better" (the targeted level of improvement to ESC Step 5) TEDI for each case listed in Table 2 is shown. Case 1, the compact house, has the lowest $TEDI_{ref}$. In this case, 50% improvement over the reference building corresponds to TEDI = 28 kWh/m^2/a. Case 2 represents a house of the same size but with more articulation in the envelope, leading to more than 20% increase in *r*. By merely adding corners, $TEDI_{ref}$ would increase by 35%, meaning a "50% better" house would also have a 35% higher thermal energy "budget". The third case shows the same house if designed as a "rancher", i.e. all living space in one storey. This one change increases *r* by 34% and TED_{ref} by 85%. Again, this means a "50% better" house, labeled as Step 5 or NZE-r, would have TEDI = 52 kWh/m^2/a, more than three times higher than the established 15 kWh/m^2/a limit. Finally, Case 4 represents a highly articulated design, with an upper floor that has a different shape than the lower floor, increasing *r* to 1.30 and $TEDI_{ref}$ by as much as 200%. This inefficient form represents a common design in Canada, which the RBA effectively incentivizes by allowing it almost three times the thermal energy budget of the comparable compact design and over five times the NZE-r limit.

5.4. Methodological peculiarities

In addition to the fundamental shortcomings of the RBA, there are methodological issues, which can vary by jurisdiction. For instance, the ERS Reference House has all the windows combined into "equivalent" windows distributed equally on the four façades. Depending on the total glazing area, sometimes the total fenestration area may also change [19]. The impact of this modeling detail is illustrated on a house designed to meet Step 5, shown in Fig. 6.

Fig. 7 illustrates two scenarios for the TEDI of the house shown in Fig. 6: i) the original design with the high-glazing façade facing north and ii) a flipped design with the highly glazed façade facing south. As expected, in the second case, the TEDI is about 25% lower, due to higher solar heat gain. However, since the "equivalent" Reference House windows are distributed identically in the two cases, $TEDI_{ref}$ does not change, as shown in Fig. 7. This gives houses with southern exposure a significant advantage over houses with northern exposure. Although the preferential treatment of certain orientations is generally favorable in a heating-dominant climate such as Canada's, it ignores the role of the energy performance of the fenestration products as well as the building as whole.

5.5. Issues in larger and non-residential buildings

Although the issues discussed above pertain to small residential buildings, similar issues exist in large buildings. While multistorey buildings generally enjoy a favorable, i.e. compact, form, there are factors that may be adversely affected by RBA. For example, the low performance of a highly glazed building can be incrementally improved with the use of better glazing. Beyond a certain point, this incremental improvement would only be possible at prohibitively high costs. A highly efficient design, on the other hand, will require the optimization of the window to wall ratio with attention to cost, energy demand, marketability, daylighting,

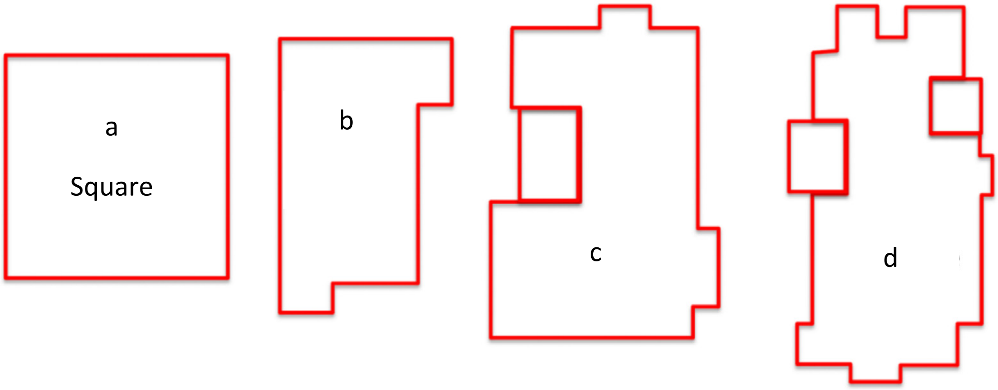

Fig. 4. Envelope surface area to Volume of sample floor plans as ratio having the same floor area.

Table 2
Summary of the formal charachtersitics of the four example desings.

	Conditioned floor area [m^2]	Number of storeys	Conditioned volume [m^3]	Envelope surface area [m^2]	Envelope area to volume ratio, r [m^{-1}]	Major design feature
Case 1	132	2	722	531.56	0.74	Efficient (compact) form
Case 2	132	2	722	653.57	0.91	Typical track or spec house design
Case 3	132	1	722	869.78	1.20	Rancher (one storey)
Case 4	132	2	722	914.11	1.27	Expensive custom house

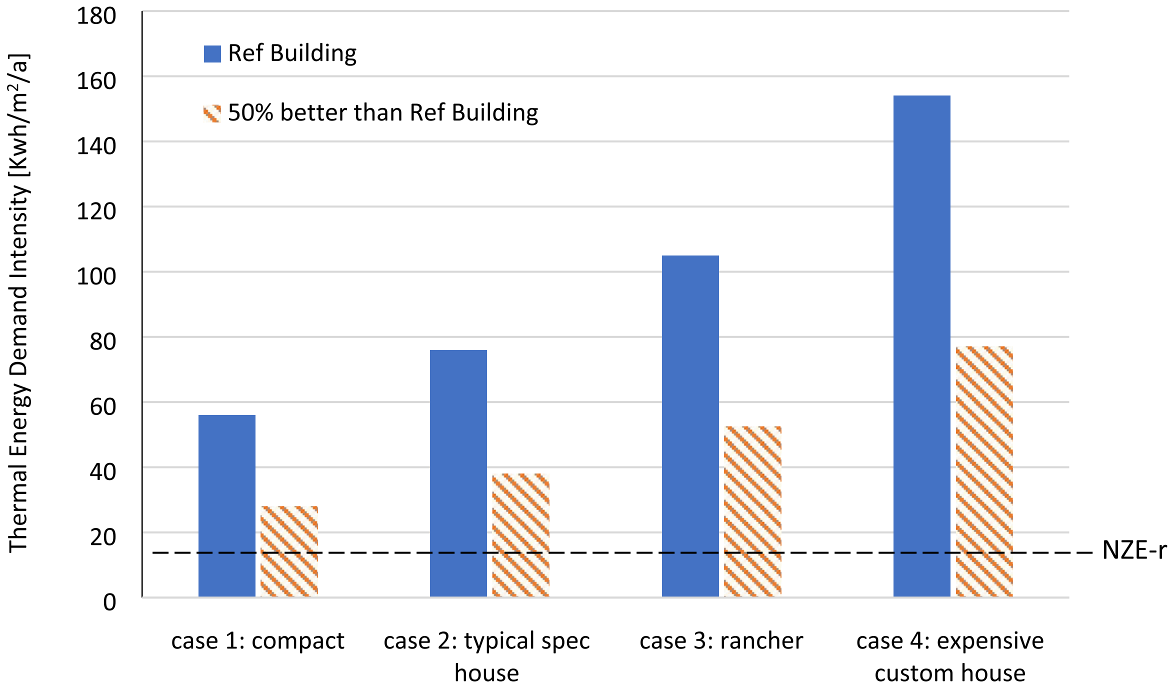

Fig. 5. Thermal Energy Demand Intensity of the EnerGuide Reference Building *(TEDI$_{ref}$)* in four typical designs having the same floor area, but different shapes (form factors). The 50% improvements over *TEDI$_{ref}$* in each case as well as the net-zero energy ready level (NZE-r) are also shown.

Fig. 6. A sample house designed to Step 5 of the Energy Step Code. Left: South Elevation, right: North Elevation.

natural ventilation, etc. In addition, architectural design, including the shape of the building, may be altered to improve natural ventilation and reduce mechanical ventilation and cooling loads, or stairs made more attractive to reduce the number of elevators. The RBA does not reward such design choices. Moreover, the RBA could be even more “attractive”, and possibly more problematic, for multi-unit residential buildings (apartments and row houses) where the smaller unit floor area makes it more challenging to meet the energy use intensity targets.

5.6. Discussion

Based on the results presented above, the shortcomings of the RBA can be summarized as follows:

a. Required levels of efficiency are not achieved

The RBA is not an effective tool in driving the highest levels of energy efficiency, particularly the NZE-r limit of 15 kWh/m^2/a. It is not clear how, if at all possible, the relative performance targets

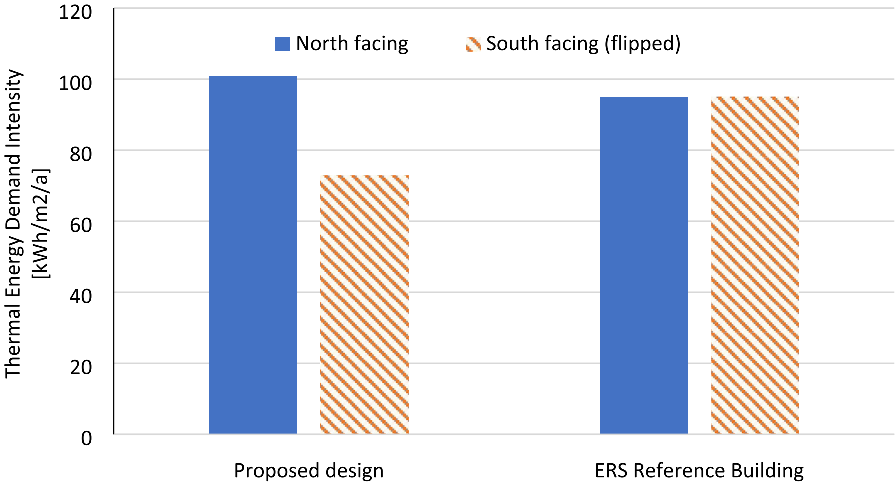

Fig. 7. The thermal energy demand of the house shown in Fig. 6 with the high-glazing façade facing south or north.

of RBA are to be reconciled with measurable, concrete metrics, e.g. the 15 kWh/m^2/a target.

b. The sliding scale

The RBA creates a sliding bar: depending on design, most importantly form and orientation, reference buildings of the same archetype and floor area can have widely different energy performances. Therefore, a certain percentage improvement over the respective reference building may correspond to widely different energy demands in absolute terms. Consequently, even ambitious improvement targets such as "50% better than the Reference House" do not guarantee NZE-r outcomes.

c. Favors inefficient designs

The RBA relies on a baseline with the same shape and size, i.e. form, as the proposed house, with no provisions on the area to volume ratio (form factor), a fundamental design parameter. As a result, not only does RBA not prohibit inherently inefficient designs with excessive articulation in the envelope, it incentivizes such inefficient forms: it is easier to improve the energy performance of an inefficient design than it is to achieve absolute targets such as 15 kWh/m^2/a thermal energy demand intensity.

d. Open to manipulation and gaming

The RBA is prone to gaming or manipulation. There are well known "hacks" that can be used to lower the energy performance of the reference building, hence making it easier to improve upon that degraded baseline. While the specific hacks mentioned in this paper may be unique to HOT2000 and ERS in Canada, conversations with practitioners in other jurisdictions indicate comparable anomalies exist elsewhere. Some of these anomalies arise from the desire to develop simple modeling and reporting procedures that apply as broadly as possible, but oversimplification can compromise accuracy.

e. Increases the cost and complexity of energy modelling

The RBA adds complexity and cost to the design process by requiring the creation of two energy models for one building – the reference building and the actual building. Both models will have to be modified and updated as the design evolves. Furthermore, the RBA modeling and reporting procedures are generally more cumbersome than those required for showing compliance with absolute metrics. For instance, the ESC's relative envelope performance metric and the associated calculation methodology [78] are unnecessarily complicated and cumbersome, requiring arbitrary adjustments to the building energy model which lack rigor. See references [45,78] for details. These unnecessary complexities impede informed use of building energy modeling as a decision-making tool and the integrated approach to design.

f. Widens the performance gap

It has been well documented that the performance gap is larger for buildings with higher energy demand, e.g. [29,81,82]. Therefore, by allowing higher energy demand/use intensities, the RBA can exacerbate the performance gap. Given the proliferation of building energy modeling and the increasing use of modeling data in the design and evaluation of efficiency programs, the increase in the performance gap can further distance policies from reality and render them ineffective. This can also lead to a situation where policies are, on paper, deemed "effective", e.g. by reporting a percentage improvement over "historical norms" (supposedly represented by reference buildings), while the actual performance of the buildings stagnates or even deteriorates [45].

One important factor in exacerbating the performance gap is that RBA is concerned with code compliance, not accurate prediction of the operational energy use of buildings. As a result, various standardized assumptions and loads are inputted into the energy model rather than estimated actual loads for the proposed building. Furthermore, the actual energy performance of the proposed building is not regulated; the modelling approach is only meant to provide compliance statements.

g. Misguides costing studies

By allowing and favoring inefficient designs, the RBA can also misguide costing studies that are typically carried out in preparation for the roll-out of new regulations or requirements. Making an inherently inefficient building perform better by adding insulation or higher-efficiency systems is inevitably an expensive endeavour. On the other hand, an efficient design can achieve NZE-r performance relatively easily and inexpensively. By identifying costs associated with incremental improvements to inefficient designs, costing studies based on the RBA tend to overestimate the cost of efficiency.

h. Impedes housing equity

The adverse impacts of RBA go beyond energy efficiency. By favoring inefficient designs with large form factors, the RBA effectively requires affordable housing, which typically has more compact form, to perform better (in absolute terms, kWh/m^2/a) than luxury houses with sophisticated designs and a high degree of articulation in the envelope. This is a fundamental and unacceptable exacerbation of the disproportionate climate impacts of higher-income households.

6. Conclusion

Efficiency is the first fuel; decarbonizing the building sector requires first minimizing the energy demand of buildings. A global consensus is emerging around 15 kWh/m^2/a thermal energy demand as a benchmark for net-zero energy ready performance. The imperative to deliver net-zero energy buildings calls for close examination of the effectiveness of policies and regulations that are meant to mandate and deliver such buildings. The present paper examined the Reference Building Approach which is a compliance option in several building energy codes and standards, especially in North America.

Analysis of energy modeling data from houses built to the Energy Step Code reveals fundamental shortcomings in the RBA and a significant gap between the absolute performance targets of ESC and the relative targets based on RBA. Most importantly, RBA creates a sliding scale with different performance targets for each single building and favors inherently inefficient design, especially non-compact buildings with large envelope surface area. In addition, it can widen the performance gap, impede effective use of energy modeling as a design tool and hinder housing equity.

While the details of how the RBA is applied vary between jurisdictions, leading to possibly different outcomes, the underlying issues remain. Although this paper was confined in scope to small residential buildings, issues also arise if the RBA is applied to larger buildings. Careful assessment of the effectiveness of the RBA for larger buildings is a topic for future work.

In summary, the RBA is an ineffective approach, unsuited to the requirements of a modern building energy code seeking to deliver the highest levels of energy efficiency. Although the use of RBA cannot be singled out as the sole barrier to high-performance buildings, it is sufficient to render a building energy regulation ineffective. Given the issues identified in this paper, the discontinuance of the RBA as a code compliance option is recommended.

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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