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Energy performance criteria for residential buildings: A comparison of Finnish, Norwegian, Swedish, and Russian building codes

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ABSTRACT

Building code are considered to be an effective policy tool to reduce energy use in buildings. In practice, national priorities influence the indicators and criteria adopted in the building codes. Consequently, neighbouring countries with similar climate conditions may use different criteria in their building codes to regulate the energy performance. In this paper, the energy performance criteria and their relative stringency in the latest residential building codes of Finland, Norway, Sweden and Russia are compared. The study is based on energy performance evaluations of one single-family building and one multi-family building, located in the north of Sweden. Both buildings complied with the Norwegian and Russian building code. However, the buildings did not comply with the *specific fan power* and *heat loss* criteria in the Finnish building code. Additionally, the single-family building did not comply with the *specific primary energy* and *electric powerdemand* criteria in the Swedish building code when heated by an electric heater. The national standard input data were found to have a large influence on the buildings' compliance with the studied energy use criteria. Policy implications of the results are discussed.

1. Introduction

The residential sector offers a significant cost-effective energy use reduction potential in Europe [1]. Governments often use a mix of policy instruments to reduce energy use in buildings. Regulatory instruments have been found to be effective in reducing the energy use in buildings [2,3]. Building codes that stipulate energy performance criteria is a widely applied regulatory policy tool [4] to improve the energy efficiency in buildings. EU directive 2010/31/EU on the energy performance of buildings (recast) is one of the driving factors for energy efficiency improvement of buildings in Europe [5]. According to EPBD, all new buildings should be "nearly zero-energy buildings" (nZEB) from 2021. As per article 2 in the directive, nZEB are buildings that have a very high energy performance. It is the responsibility of the member states to provide numerical quantification/threshold values for "very high energy performance" [6]. EPBD stipulates that the member states shall define nearly zero-energy buildings based on the situation in the respective countries while providing a criterion for yearly primary energy use in kWh/m^2 [6]. Further, EPBD directs that the requirements should be set to achieve an optimal balance between investment cost and energy savings [7].

Annunziata et al [8] studied the national regulations in Europe and national adoptions of the EPBD recast and found that European countries have embraced different approaches in their national regulatory framework to incorporate the EPBD recast. A review of national building codes in eight European countries showed that different indicators were used to set requirements on building energy performance in those countries [9]. Similarly, Thuller [10] found that different indicators were used to set national criteria for low-energy buildings in nine European countries. A review of nZEB definitions in ten EU member countries showed a large variation in primary energy use values, even for countries with similar climate, due to differences in the indicators used and ambition levels [11]. Casalas [12] has analyzed the role, limitations, and differences of building energy regulation and certification in Europe. They found that applying inappropriate indicators to assess building energy performance may prevent the building regulations and certification schemes from achieving their objectives.

This paper differentiates between indicators and criteria used in the building codes. Indicators are parameters used to monitor the performance of a building component, such as U-value for windows (W/m^{2}K) or the energy performance of the building as a system such as specific energy use (kWh/m^{2}year). Criteria are the maximum/minimum required values for the indicators used to regulate building energy performance, such as a maximum specific energy use of 90 kWh/m^{2}year and a maximum U-value for win-

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dows of 1.2 W/m^{2}K. There may be advantages and disadvantages of using different indicators and criteria to regulate the energy performance of buildings. Thus, the choice of indicators and criteria could have consequences for the built environment and a country's progress towards improving the energy performance of its buildings. For example, indicators and criteria focused more on the technical installations than the heat loss of the building envelope may incentivize energy efficient installations but not energy efficient building materials and construction methods. Comparisons of building energy performance criteria may facilitate benchmarking of such criteria. For example, benchmarking of EPBD applications in different countries, or to compare the latest version of a national building code with its older versions. Further, even small differences between the building codes of countries could be a barrier for the building industry to expand their business across national borders [13]. Consequently, the need for harmonization of the national building energy codes is frequently expressed by the building industry in Europe [13,14]. Comparing the energy performance criteria used in different national building codes may provide opportunities to learn from different strategies for improving building energy performance and may facilitate actions towards such harmonization.

In Europe, the indicators used to regulate building energy performance vary between countries. The 2018 Danish building code, for example, regulates primary energy use, the envelope air leakage, the overall envelope transmission heat loss (excluding windows and doors), and U-values for envelope components [15]. The 2017 Norwegian building code regulates U-values for envelope components, envelope air leakage, and net energy use (or alternatively thermal bridges, window area to heated floor area, specific fan power, and ventilation heat recovery efficiency) [16]. Many countries have implemented a primary energy use indicator as per EPBD [17]. However, the primary energy use indicator is expressed in different units such as kWh/m^{2}year, CO_2 emissions, or a "primary energy performance coefficient" [17]. The energy usage included in the primary energy use indicator (e.g. energy for space heating/cooling and domestic hot water) and the weighting factors used to calculate the primary energy use also differ among countries. The member states may also use various other indicators in their adaptation of EPBD, such as U-values, heating energy demand, supplied energy, system efficiencies, envelope air leakage, and installed power [17].

Literature on comparisons of energy performance criteria in building codes is scarce. Asdrubali et al. [18] compared the building energy regulations of Italy and Spain, and as per their study the Italian regulations were more stringent. Lee and Chen [19] compared the building energy regulations of Hong Kong and China and the results indicate that the Chinese regulations were more restrictive. Wang et al. [20] compared the energy regulations in China and UK and found that strengthening the Chinese requirements to the regulation level in UK could reduce energy use in Chinese buildings. Fayaz and Kari compared the energy regulations in Turkey and Iran [21] and found that the minimum required thermal insulation according to the Iranian regulation were much lower than that of the Turkish regulation. These studies compare the building code of one country against another country. To the best of the authors' knowledge no studies exist that compare building codes of several countries against each other using case study buildings.

The energy efficiency of residential buildings in Nordic countries are relatively high. For example, a study that compared the energy use of residential buildings in Europe found that Finland, Norway and Sweden are among the top 10 countries in Europe with relatively low energy use [2]. Sweden and Finland use similar policy mixes to reduce the energy use in residential sector [2]. The energy performance criteria for residential buildings in the building codes of Finland, Norway, and Sweden were reviewed in an earlier study [22]. Despite similar climate and building traditions, different indicators of building energy performance were used in these countries [22]. The use of different indicators in the national building codes makes it difficult to have cross-country comparisons of building energy performance.

The geographical focus of this study is Fennoscandia - Norway, Sweden, Finland, and the northwestern parts of Russia, which have similar climate. The energy performance regulations for buildings in Finland, Norway, and Sweden are influenced by the EPBD. However, Russian building code is not directly influenced by EPBD. The Russian building stock is also relatively less energy efficient compared to the Nordic countries [23]. The national building code of Russia was therefore included in the scope to study the energy performance criteria in countries with a similar climate but with different energy baseline and building regulations. The objective of this study is to compare the stringency and scope of the energy performance criteria in the building codes of these four countries. The study is based on simulations of two residential buildings - one single-family house and one multi-family building.

2. Energy performance criteria in national building codes

Different criteria on building energy performance may influence the technological and societal development in different directions, introducing different practices and norms of living conditions and comfort [24]. There are two main strategies for regulating building energy performance (i) prescriptive/component requirement models and (ii) performance/whole-building requirement models [17,25,26]. Component-focused requirements regulate properties of specific components of the building and its energy system. The components may be building elements (such as windows or walls), technical installations, or aspects of the building design (such as the form factor). The properties of such components are often provided in product specifications and, therefore, compliance with component-focused requirements often donot require much analysis to evaluate [25]. Whole-building requirements such as maxiumum energy use or overall heat loss regulate the energy performance of the building as a system within a specified system boundary. For example, the *specific supplied energy* indicates the combined performance of all building properties influencing the amount of energy supplied to the building. Such system-focused requirements reflect broader energy efficiency goals and require more complex evaluation methods [24,25]. Experiences from implementing the EPBD directive in EU countries imply that a combination of system-focused and component-focused requirements might be optimal for energy performance criteria to ensure a holistic approach to energy savings in the building stock [27].

The energy performance indicators used in the building codes of countries in Europe are based on two European standards on building energy performance ratings and indicators: CEN - EN 15603 [28] and CEN - EN 15217:2007 [29]. These standards allow for the use of both energy use indicators and other types of indicators such as envelope air leakage and U-values of envelope components. Hence, the national building codes in European countries today use many different indicators to regulate energy performance. Similarly, the requirements for specific indicators vary between different countries. In this paper, the energy performance indicators in the building codes are divided into (i) energy use indicators and/or (ii) "other" indicators. The "other" indicators are component focused indicators such as *envelope air leakage, heat transfer coefficients (U-values)* or system focused indicators such as *electric powerdemand* and *heat loss factor*.

2.1. The building codes

The energy performance criteria in the following national building codes were compared:

- The Finnish 2017 building code [30]
- The Norwegian 2017 building code [16]
- The Swedish 2019 building code [31]
- The Russian 2012 building code [32]

In the last decade, in order to align the national building code to EPBD, Sweden and Finland have made modifications a few times in their building code and made partial progress in defining nZEB [6]. The energy performance criteria for building envelope components in the Finnish and Swedish building code were similar a decade ago [2]. Finland has modified its building code three times during the last decade: in 2010, 2012 and 2017. One of the main changes in the Finnish building code happened in 2012 when an energy use criterion was introduced. Further, the most recent building code from 2017 excluded the criteria on envelope component U-values, window to floor area, and ventilation heat recovery efficiency, while adding a requirement on specific fan power. The Swedish building code has also undergone several modifications on energy performance indicators and criteria in the last decade: in 2011, 2015, 2017, and 2019. For example, the requirement on *specific supplied energy* use in the 2015 Swedish building code [33] was changed to *specific primary energy* use in the 2017 building code [34]. Similarly, the 2015 building code categorized Sweden into four climate zones for energy use while the latest Swedish building code has 52 climate zones [31]. The 2019 Swedish and 2019 Finnish building codes both use a *specific primary energy* indicator to regulate buildings' energy performance. However, they also use different additional indicators (refer Table 1).

Although Norway is not an EU member state, it has chosen to collaborate with EU in the adaptation of EPBD [17]. Hence to a certain extent the Norwegian building code may also be influenced by the EPBD. The building code in Norway was modified twice during 2010–2020, lately in 2017. However, the energy performance criteria in the Norwegian building code has undergone only minor modifications during this period. Similar to Finland and Sweden, Norwa also uses one specific energy use indicator in combination with other indicators in the building code. However, while Finland and Sweden use a *specific primary energy* indicator, Norway use a *specific net energy* indicator. To regulate the energy supply system, the Norwegian building code prohibits the use of fossil fuel for heating.

The Russian building code has been undergoing a transformation during the last decade with the aim to simplify the regulatory system. According to a federal law on technical regulation [35], the energy performance criteria in the Russian national building code (SNIP 23–02-2003) got an advisory status after 2009 [36]. However, in 2010 the Federal Government approved a list of mandatory national standards and codes, including SNIP 23–02-2003 [37]. This list was updated in 2014, replacing SNIP 23–02-2003 with the updated 2012 version [37]. However, only a few of the energy performance criteria in the 2012 version of the Russian building code were specified in this list and thus have mandatory status (Section 1, Section 4.3 and 4.4, Section 5.1, 5.2, 5.4–5.7, Section 6.8, Section 7.3, subparagraphs "a" and "b" of section 8.1, section 9.1. and Annex D) [38]. In this study the mandatory energy performance criteria in the 2012 Russian building code were compared to the other national building codes.

2.2. Energy performance criteria in the Finnish, Norwegian, Swedish, and Russian building code

The energy performance criteria for single-family and multi-family buildings differ in the studied national building codes (Table 1). A combination of energy use indicators and "other" indicators are used for residential buildings in the national building codes of Finland, Norway, and Sweden (Table 1). For example, the 2019 Swedish building code [31] has requirements on *specific primary energy* and "other" indicators such as *envelope U-value* and *electric powerdemand.* However, the Russian building code does not regulate energy use and only has requirements on "other" indicators such as building component U-values. The 2017 Norwegian building code [16] provide two alternative ways for evaluating building energy performance where (i) has both energy use and "other" indicators (alternative 1), and (ii) has only criteria on "other" indicators (alternative 2). The criteria on U-values for building envelope components and envelope air leakage in alternative 2 are more stringent than in alternative 1. For alternative 2, if the building does not comply with one of the criteria in Table 1 related to the buildings' overall heat loss (such as U-values for envelope components), it is still possible to show compliance if the calculated overall heat loss from the building is within a reference heat loss value. The reference heat loss is calculated based on the minimum requirements for the individual criteria related to the buildings' overall heat loss. However, in such cases, the building should still comply with the minimum criteria on U-values and envelope air leakage in alternative 1.

The *specific primary energy* indicator is calculated by multiplying the *specific supplied energy* with nationally defined weighting factors [28]. These weighting factors represent the energy losses from the primary energy source to the supplied energy. However, renewable energy contributions may be excluded in determing the weighting factors which may result in a weighting factor less than 1. The *specific primary* indicator used in Finland and Sweden and the *specific net energy* indicator used in Norway have different system boundaries. The system boundaries include different aspects of a buildings' energy performance such as the behavior of occupants, building operation, the building envelope and the installations for energy production on and outside the building property.

In addition to the different system boundaries, energy use for different purposes are also included in the specific energy use indicators (Table 3). Among the studied specific energy use indicators, the Finnish *specific primary energy* indicator covers energy use for the most purposes (Table 2). Illustrations of the system boundaries and energy use included in the specific energy use indicators in Finnish, Norwegian, and Swedish building codes are provided in Fig. 1 a-c. In the figure, the parts of the building's energy balance included in respective indicator are shown in grey colour, while the excluded parts are shown in white colour. The dashed lines indicate the system boundaries. In the 2017 Finnish and 2019 Swedish *specific primary energy* indicators, renewable energy extracted at the building site such as energy from the sun, ground, and air is not counted (weighting factor = 0). Further, energy produced by wind at the building site is also not counted in the 2017 Finnish *specific primary energy* indicator.

Another difference between the studied building codes is how compliance with the specific energy use criteria is evaluated. In Finland and Norway compliance is evaluated only through calculations (although measurements in the operational phase are required for other purposes, such as energy certification). As per the Swedish building code, compliance with the criteria must be evaluated both through calculations (e.g. simulations) in the design phase and by measurements in the operational phase [45].

3. Method

As a few energy performance criteria in the national building codes of the four countries differ for single-family and multi-

Table 1
Energy performance criteria in the building codes for the single-family and multi-family buildings.

Building code	Energy use indicators	Requirement	"Other" indicators	Requirement
2017 Finnish building code [30]	*Specific primary energy*[a] single-family building multi-family building	$\le$ 107 kWh/ m^2_{floor}year $\le$ 90 kWh/ m^2_{floor}year	*Envelope air leakage* [b] *Specific fan power* *Heat loss* [c] single-family building multi-family building	$\le$4.00 m^3/hm^2_{env} $\le$1.80 kW/(m^3/s) $\le$ 187 W/K $\le$ 1021 W/K
2017 Norwegian building code [16] - alt. 1	*Specific net energy* [d] single-family building multi-family building	$\le$108 kWh/ m^2_{floor}year $\le$ 95 kWh/ m^2_{floor}year	*U-value for walls* [e] *U-value for roof* [e] *U-value for floor* [e] *U-value for windows/doors*[e] *Envelope air leakage* [b] single-family building multi-family building	$\le$0.220 W/ m^2_{env}K $\le$ 0.180 W/ m^2_{env}K $\le$ 0.180 W/m^2_{env}K $\le$1.20 W/m^2_{env}K $\le$1.5 h^{-1} $\le$ 1.64 m^3/ hm^2_{env} $\le$ 3.21 m^3/hm^2_{env}
2017 Norwegian building code [16] - alt. 2			*U-value for walls* [ef] *U-value for roof* [ef] *U-value for floor* [ef] *U-value for windows/doors* [ef] *Window area/heated floor area* [f] *Thermal bridges* [f] single-family building multi-family building *Envelope air leakage* [bf] single-family building multi-family building *Ventilation heat recovery temperature efficiency* *Specific fan power*	$\le$0.18 W/m^2_{env}K $\le$0.13 W/m^2_{env}K $\le$0.10 W/m^2_{env}K $\le$0.8 W/m^2_{env}K $\le$ 25 % $\le$ 0.05 W/(m^2K) $\le$ 0.07 W/ (m^2K) $\le$0.6 h^{-1} $\le$ 0.656 m^3/ hm^2_{env} $\le$ 1.28 m^3/hm^2_{env} $\ge$80.0 % $\le$ 1.5 kW/(m^3/s)
2019 Swedish building code [31]	*Specific primary energy* [g] single-family building multi-family building	$\le$90.0 kWh/ m^2_{floor}year $\le$ 85.0 kWh/ m^2_{floor}year	*Envelope U-value* [h] *Electric powerdemand* [i] single-family building multi-family building	$\le$0.400 W/m^2_{env}K $\le$ 7.58 kW $\le$ 47.3 kW
2012 Russian building code [32]	–		*U-value for walls* [j] *U-value for roof* [j] *U-value for floors* [j] *U-value for windows/doors* [j] *Envelope U-value multiplied by form factor* single-family building multi-family building	$\le$0.328 W/m^2_{env}K $\le$0.219 W/ m^2_{env}K $\le$ 0.249 W/m^2_{env}K $\le$1.99 W/m^2_{env}K $\le$ 0.461 W/m^3K $\le$ 0.261 W/ m^3K

[a] Per floor area heated above 17 °C. Calculated by multiplying the supplied energy with a primary energy factor 1.2 for electricity, 0.5 for district heating, 0.28 for district cooling, 1.0 for fossil fuels, and 0.5 for renewable fuels
[b] At 50 Pa
[c] Envelope heat losses through heat transfer, ventilation, and air leakage
[d] Per floor area in spaces with an installed space heating system
[e] Overall heat transfer coefficients for specific building parts
[f] The criteria may be exceeded as long as the influence on the overall heat loss of the building envelope is counteracted in other indicators so that the overall heat loss is not increased
[g] Per floor area heated above 10 °C. Excluding supplied geothermal- and solar energy. Calculated by dividing the supplied energy for space heating by a geographical adjustment factor and multiplying the total supplied energy with a primary energy factor 1.6 for electricity, and 1 for all other energy carriers/sources
[h] Overall heat transfer coefficient for building envelope
[i] Electric power demand for space heating and domestic hot water preparation required at DVUT
[j] Converted from m2K/W

Table 2
Types of energy use included in the energy use indicators in the studied building codes.[*]

	2017 Finnish building code	2017 Norwegian building code	2019 Swedish building code
Indicator Energy use included	*Specific primary energy*	*Specific net energy*	*Specific primary energy*
Space heating	x	x	x
Space cooling	x	–[a]	x
Domestic hot water	x	x	x
Facility appliances	x	x	x
Household appliances	x	x	–

[*] Russian building code does not have energy use indicators
[a] Space cooling is not allowed in Norwegian residential buildings as per Norwegian building code [16]

Table 3
Design specific input data for the single-family building.

Parameter	Value
Floor area heated above 10 °C (m_{floor})	213 m^2
Envelope area	542 m^2
Volume	593 m^3
Window area	35.1 m^2
U-value for the external walls	0.17 W/(m^2K)[a]
U-value for the roof	0.06 W/(m^2K)[b]
U-value for the foundation	0.10 W/(m^2K) [c]
U-value for the windows	1.2 W/(m^2K) [d]
Ventilation system	Supply- and exhaust system with a plate heat exchanger with frost protection and an electric heater for pre-heating of the supply air
Ventilation heat exchanger temperature efficiency	80 %
Shading	External shading caused by protruding roof

[a] Stud walls with 285 mm mineral wool, wooden panel
[b] 600 mm loose wool insulation and concrete roof tiles
[c] 250 mm concrete slab with 300 mm foam insulation
[d] Triple-pane windows with insulation panes [40]

family buildings, one existing single-family building and one multi-family building was used to compare the building codes. The relative stringency of the energy performance criteria were compared based on the buildings' compliance with the studied building codes. The compliance with the building codes in absolute values may be different for buildings other than the case study

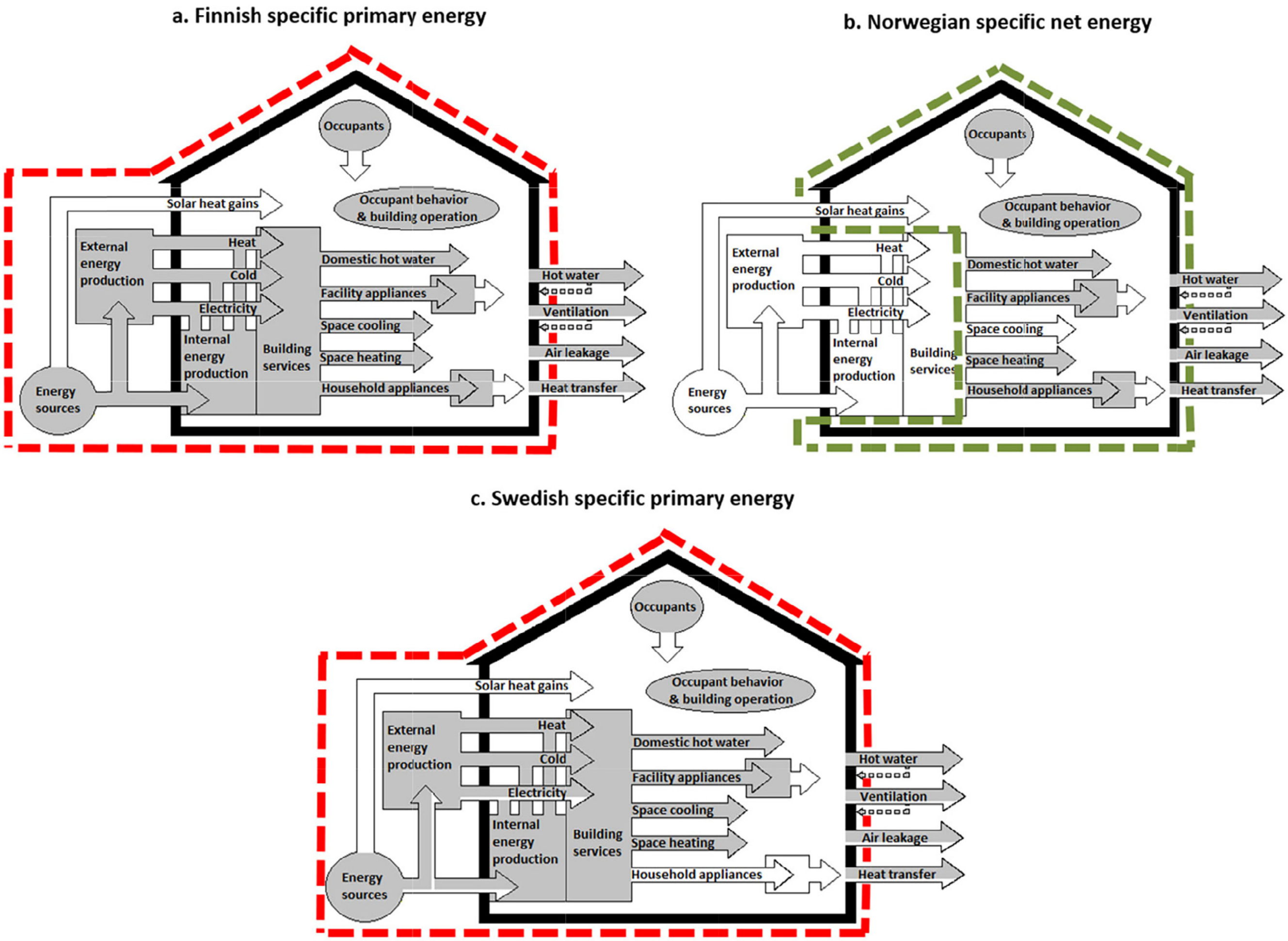


Fig. 1. Illustration of the system boundaries for the specific energy use indicators in the studied building codes, indicated by dashed lines in green and red for net and primary energy, respecitvely.

buildings. However, the relative differences between the building codes indicated by their compliance would be similar. Though this study was based on residential buildings, the method could also be used for other building categories.

The *heat loss* indicators in the Finnish and Norwegian building codes were calculated using the equations and instructions provided in the Finnish building code [30] and Norwegian standard NS 3031, respectively [39]. The buildings' *specific net energy, specific primary energy* and *electric powerdemand* was evaluated through simulation. The simulations were based on input data available in the buildings design phase (henceforth design specific input data) from blueprints and manufacturers' specifications and national standard input data (henceforth "NS_{id}") according to each country for parameters such as climate, operation, and occupant behavior. Since the envelope air leakage is unknown in the design phase, standard values for the buildings' envelope air leakage were also included in the NS_{id}. Assumptions were made for any input data not available in the design data or NS_{id}. A schematic of the method used to evaluate the energy performance of the two case study buildings according to each of the four national building codes is shown in Fig. 2. The input data is presented in section 3.1 and 3.3. To study the impact of different heat supply systems on the buildings' compliance with the criteria, four types of heat supply systems (heat pump, pellet boiler, electric heater and district heating) were studied. The heat supply systems are presented in section 3.2.

The buildings' design data, assumed data, and heat supply systems were the same in the evaluations according to all building codes. Consequently, any difference in how the buildings complied with the energy performance criteria in different national building codes did not depend on these data. However, the NS_{id} and the energy performance criteria differed among the building codes. The buildings' compliance with the building codes could therefore be influenced by both the energy performance criteria and the NS_{id}. The standard envelope air leakage values in the NS_{id} were based on maximum requirements or recommendations in the four building codes, representing a worst-case scenario in each country. Hence, the criteria on envelope air leakage, if any, in the building codes were met by default.

3.1. Case study buildings

Two residential buildings were chosen as case study buildings: a single-family building constructed in 2010 and a multi-family building constructed in 2011. The case study buildings (henceforth referred as buildings) are located in Umeå, Sweden, at latitude N 63°82′ on the border between subarctic and humid continental climate. The chosen buildings represent energy efficient buildings in Sweden from the early 2010s.

The single-family building has two floors (Fig. 3a and b). The multi-family building has four floors with apartments and a heated attic with storage (Fig. 4a and b). The design data used in the simulations of the single- and multi-family building were taken from the building blueprints and product specifications (Table 3 and 4). Input data used for other relevant parameters in the simulations

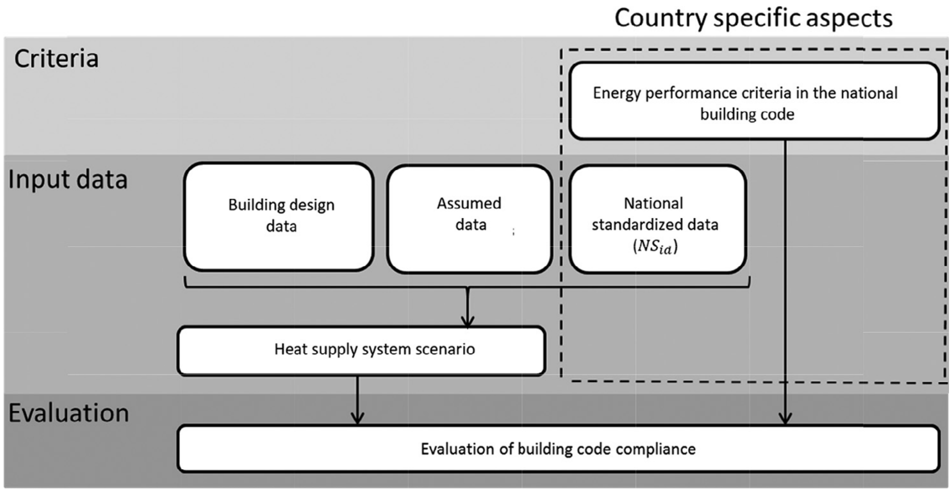
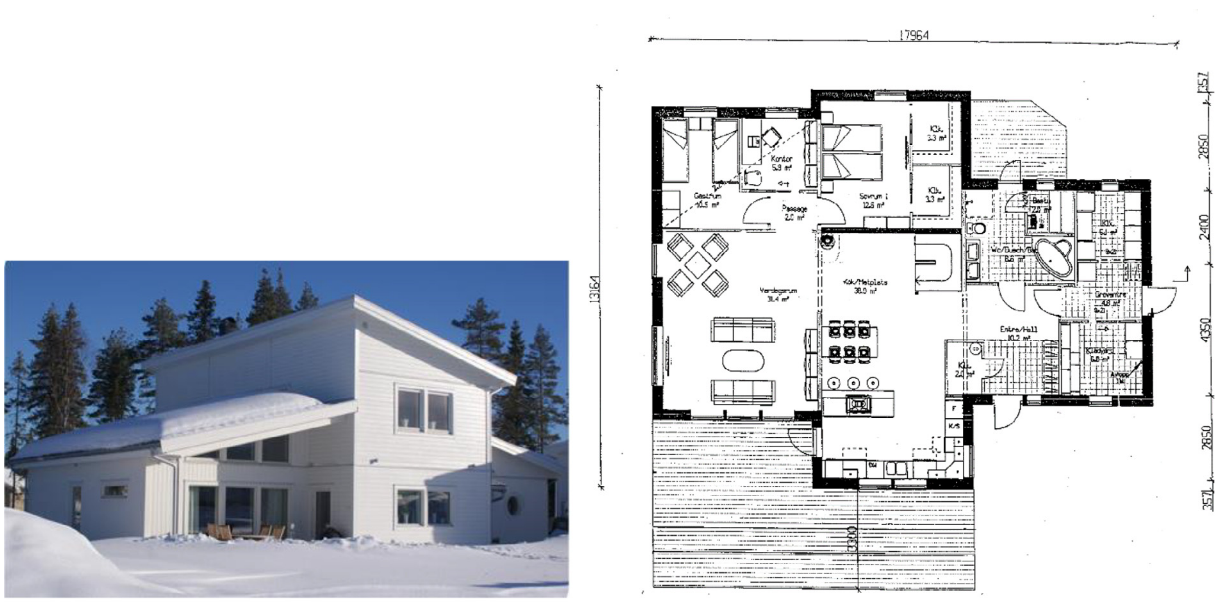


Fig. 2. A schematic of the method used for the evaluations of the case study building's energy performance according to the different building codes.



a. View of the single-family building

b. Floor plan of the single-family building

Fig. 3. a. View of the single-family building. b. Floor plan of the single-family building.

are presented in Table 5. The buildings do not have cooling systems.

3.2. Heat supply systems

The specific energy use indicators in the Swedish and Finnish building codes were calculated using different weighting factors for electricity, district heating, fossil fuels, and renewable fuels. The heat supply system for domestic hot water and space heating in the single-family case study building was a geothermal heat pump with a coefficient of performance (COP) of 5.. In the multi-family building, energy for space heating and domestic hot water was supplied by district heating. These heating sources were chosen as two of the heat supply system scenarios. The buildings were evaluated with two additional heat supply systems (i) a pellet boiler with 80 % efficiency (the lowest efficiency of 11 pellet boilers tested by the Energy Agency in Sweden [44].) and (ii) an electric heater. The heat losses from the electric heater and district heating system within the building will contribute to its space heating. Accordingly, in this study, the efficiency of the electric heater and the district heating system within the building property was assumed to be 100 % [45]. Modern space heating systems may use temperatures of 30–40 °C, while domestic hot water requires temperatures of at least 50–60 °C [46]. Since heat pump efficiency decreases with increasing input to output temperature gap, the COP was considered to be lower than specified by the manufacturer (3 instead of 5) for domestic hot water production in the heat pump scenario.

The heat supply systems only affected indicators influenced by the efficiency of the energy production or the choice of energy sources. For the *specific net energy*, all energy production is outside the system boundary (see Fig. 1 b for Norway). Therefore, the heat supply scenarios had no influence on the *specific net energy* indicator in the Norwegian building code. The Russian building code does not have an energy use indicator. Hence, the heat supply system scenarios only affected the energy use indicators in the Finnish

a. View of the multi-family building b. Elevation drawing of the multi-family building

Fig. 4. a. View of the multi-family building. b. Elevation drawing of the multi-family building.

Table 4
Design specific input data for the multi-family building.

Parameter	Value
Floor area heated above 10 °C (m_{floor})	1495 m^2
Accommodation area	1098 m^2
Envelope area	1847 m^2
Volume	3952 m^3
Window area	243 m^2
U-value for the external walls	0.127 W/m^{2}K
U-value for the roof	0.081 W/m^{2}K
U-value for the foundation	0.238 W/m^{2}K
U-value for the windows	1.20 W/m^{2}K
Ventilation system	Supply- and exhaust system with a rotary heat exchanger
Ventilation heat exchanger temperature efficiency	80 %
Elevator for the multi-family building	Gearless traction elevator [a]
Shading	External shading caused by balconies

[a] Using 50 kWh per apartment and year [41]

Table 5
Other input data used in the energy simulations for the single-family and multi-family buildings.

Parameter	Value
Specific fan power	2 kW/(m^3/s)
Wind profile	Suburban [a]
Thermal bridges	20.9 W/K/(m^2 envelope area) for the single-family building 72.4 W/K/(m^2 envelope area) for the multi-family building
Heat losses from the heating system	4 % of the delivered space heating energy, 50 % contributing to the space heating
Heat losses from the supply air ducts	1.16 W/m^2, 50 % contributing to the space heating
Ventilation fan efficiency	60 % [b]
Temperature set-point for the supply air	19 °C
Lighting in common areas in multi-family building	11 fluorescent lamps in the common areas, each emitting 25 W and in use 14 h/day

[a] Representing the case study buildings surroundings [42]
[b] [43]

and Swedish building code (*specific primary energy*, Fig. 1a and c) Among the "other" indicators, only the *electric powerdemand* indicator in the Swedish building code was influenced by the heat supply scenarios.

3.3. National standard input data (NS$_{id}$)

Data on climate, building operation, and occupant behavior are required to evaluate the buildings' compliance with energy use indicators. However, the standard input data for such parameters may differ between countries. To simulate the energy use of the buildings as per the individual building codes, NS$_{id}$ from the respective country is used (Table 6). The NS$_{id}$ was taken primarily from the national building codes, secondarily from documents referenced in the respective national building code, and lastly from national industry standards and statistics (such as the Swedish industry wide SVEBY-program [47]), scientific papers and reports. The 2012 Russian building code does not have an energy use or power demand indicator and hence no NS$_{id}$ was needed in the evaluation of the buildings according to the Russian building code.

The building codes have different approaches to handle climate differences within the country. For example, according to the Norwegian and Finnish building codes, climate data from the respective capital cities (Oslo and Helsinki) should be used for energy use calculations/simulations regardless of the buildings' location. The Swedish building code categorizes the country into 52 climate zones with different geographical adjustment factors. Climate data from the buildings' actual location for a normal year is used when evaluating compliance with the energy use criterion and a nationally defined geographical factor for the building's climate zone is used to adjust the resulting energy use for space heating.

Standard climate data is referred to in some of the studied building codes: hourly values are included in the standard NS 3031 [39] used according to the Norwegian building code, while monthly values are included in the Finnish building code. The meteorological database Meteonorm 7 [48] was used as source for the climate data used in this study as it fulfilled the requirements on climate data in all studied building codes. The climate data used was the average outdoor temperature and solar radiation for the period 2000–2009 and 1986–2005, respectively.

3.4. Energy simulation

Forward modeling methods are applicable in situations when building design data are available, which make them especially suitable in the building design phase [26,41]. Both dynamic and steady state forward modeling methods are commonly used to show compliance with energy performance criteria. However, dynamic modeling provides higher accuracy and allows for more

Table 6
NS_{id} used to calculate the specific energy use indicators in the building codes.

Parameters	Unit	2017 Finnish building code [30]	2017 Norwegian building code [16,39]	2019 Swedish building code [30,45]
		Single/Multi family building	Single/Multi family building	Single/Multi family building
Location for climate data (average temperature)		Helsinki (6.0 °C)	Oslo (5.6 °C)	Umeå (4.0 °C)
Envelope air leakage	[m^3/hm^2_{env}]	4.00[a]	1.64[b]/3.21[b]	2.20[c]
Indoor temperature	[°C]			
Day	[l/sm^2_{floor}]	21.0	21.0	21.0
Night (22–06)		21.0	19.0	21.0
Ventilation rate		0.400/0.500	0.333	0.350
Internal heat gains	[W/m^2_{floor}]	3.40/5.10	4.00	3.61/4.21
From household appliances		2.20/3.30	2.50	2.39
From occupants	[W/m^2_{floor}]	1.20/1.80	1.50	0.767/1.25
Energy for household appliances		2.40/3.30	3.30	3.42
Excluding lighting		1.80/2.40	2.00	–
Lighting		0.600/0.900	1.30	–
Energy use for domestic hot water	[kWh/m^2_{floor}, year]	35.0	29.8	20.0/25.0

[a] Should be used in performance evaluations according to the building code if the air tightness is not measured or demonstrated in some other way. Representing a worst-case scenario
[b] Highest allowed according to building code. Representing a worst-case scenario
[c] No standard input data is available for air leakage in the 2019 building code. A requirement from the 2011 and 2015 building codes (for buildings with less than 100 m2 floor area) was used instead, to represent a minimum building standard in Sweden

detailed comparisons of the results. Detailed simulation is a commonly used dynamic forward modeling method, as evident by the many simulation programs developed for this purpose [48–51]. Forward modeling simulation programs create a thermodynamic building model using fundamental engineering principles, expressed through mathematical algorithms [26]. The input data may be based on measurements or standard values for user behavior, operation, and climate. When the simulation is based solely on standard input data it is a purely calculation-based evaluation approach.

The energy use and power demand of the buildings was evaluated through dynamic simulation, using the multi-zone dynamic simulation program IDA Indoor Climate and Energy (IDA ICE) version 4.6.2. IDA ICE is a widely used simulation program for energy performance analysis in Finland, Norway, and Sweden. It has been validated with respect to the CEN standard EN 15265–2007 and found to have a 10 % uncertainty for simulating energy use for space heating [52]. IDA ICE has been compared to other simulation tools [52,54] and found to perform well [55]. More information about IDA ICE can be found in [42] and specifically about the IDA solver in [56].

4. Results and discussion

The results of the energy performance evaluations of the two buildings according to the four national building codes are presented in Tables 7–10. In order to compare the buildings' compliance with different criteria, the evaluation results are additionally presented as "result-to-requirement" ratios (denoted as "Ratio" in the Tables 7–10). This is the ratio between the evaluation results for the evaluated indicators and their corresponding requirements in the building code. A "result-to-requirement" ratio higher than unity indicates that the building was unable to meet that specific criterion (highlighted in the Tables 7–10).

Table 11 provides a summary of the case study buildings' compliance with the energy performance criteria in the building codes. The buildings complied with the Russian building code, and with the Norwegian building code (when evaluated as per the alternative 1). However, the buildings did not comply with the *specific fan power* and *heat loss* criteria in the Finnish building code (Table 8). The single-family building did not comply with the *specific primary energy* and *electric powerdemand* criteria in the Swedish building code when heated by an electric heater.Table 12.

4.1. Finland

The *heat loss* for the single-family and multi-family building was found to exceed the maximum allowed *heat loss* by 10 % and 11 %, respectively (Table 7). The evaluation was based on standard input data for the envelope air leakage. However, according to the Finnish building code [30], a lower envelope air leakage may be used in energy performance evaluations if proven by air-tightness protocols during the construction or by measurements. Thus, measurements of envelope air leakage (if resulting in a lower air leakage than the standard value) or the use of air tightness protocols during the construction process may have allowed the single-family building to achieve compliance with the *heat loss* criterion. However, a separate analysis showed that the multi-family building would exceed the maximum allowed *heat loss* by 1 % even with no air leakage. Compared to the criteria in the other building codes, the "result-to-requirement" ratio for the *heat loss* criterion in the Finnish building code was found to be high. Due to the tough requirement on the heat loss through the building envelope, the energy performance criteria in the Finnish building code could be inferred to be the most stringent among the studied building codes.

The Finnish *specific primary energy* indicator has a wide system boundary (Figure 1) and includes energy use for more purposes (Table 2) compared to the specific energy use indicators in the Norwegian and Swedish building codes. Hence the Finnish energy use indicator covers more aspects of a building's energy performance than the energy use indicators in the building codes of Norway and Sweden. If heated by electricity, both buildings did not comply with the *specific primary energy* criterion in the Finnish building code. This is due to a higher weighting factor used for electricity (1.2) as compared to district heating and renewable fuels (0.5) to calculate the *specific primary energy* indicator in the Finnish building code. The *specific primary energy* indicators "result-to-requirement" ratio for the two buildings when heated by an electric heater was higher (1.23 and 1.30 for the single and multi-family building, respectively) than for any criteria in the other building codes. Thus, the Finnish building code can also be considered especially strict for buildings heated by electricity.

Table 7
Results for the buildings and its compliance with the energy performance criteria in the Finnish building code.

		Unit	Single-family building			Multi-family building		
			Result	Requirement	Ratio	Result	Requirement	Ratio
Energy use indicator	*Specific primary energy* [a]	[kWh/ m²year]						
	Heat pump scenario		60.5	≤ 107	**0.57**	66.8	≤ 90	**0.74**
	Peller boiler scenario		88.1	≤ 107	**0.82**	83.8	≤ 90	**0.92**
	Electric heater scenario		132	≤ 107	**1.23**	117	≤ 90	**1.30**
	District heating scenario		78.0	≤ 107	**0.73**	76.5	≤ 90	**0.85**
"Other" indicators	*Envelope air leakage* [b]	[m³/hm$_{env}$²]	4.00[c]	≤4.00	**1.00**	4.00[c]	≤4.00	**1.00**
	Heat loss [bd]	[W/K]	205	≤ 187[e]	**1.10**	1135	≤ 1021[e]	**1.11**
	Specific fan power [a]	[kW/(m³/s)]	2	≤1.80	**1.11**	2	≤1.80	**1.11**

[a] Energy for space heating and cooling, facility electricity, domestic hot water, and household appliances.
[b] For all studied heating scenarios.
[c] Assumed as the maximum permissible envelope air leakage according to the building code.
[d] Envelope heat losses, through heat transfer, ventilation, and air leakage
[e] Calculated based on a reference building, using standard values for air leakage, ventilation heat exchanger temperature efficiency, window to floor area ratio, and U-values [30].

Table 8
Results for the buildings and its compliance with the energy performance criteria in the Norwegian building code.

		Unit	Single-family building			Multi-family building		
			Result	Requirement	Ratio	Result	Requirement	Ratio
Alt. 1 Energy use indicator	*Specific net energy* [a]	[kWh/ m²year]	95.9	≤108	**0.89**	90.9	≤95.0	**0.96**
"Other" indicators	*U-value for walls*	[W/m²K]	0.170[b]	≤0.220	**0.77**	0.130[b]	≤0.220	**0.59**
	U-value for roof	[W/m²K]	0.060[b]	≤0.180	**0.33**	0.080[b]	≤0.180	**0.44**
	U-value for floor	[W/m²K]	0.100[b]	≤0.180	**0.56**	0.170[b]	≤0.180	**0.94**
	U-value for windows/doors	[W/m²K]	1.20[b]	≤1.20	**1.00**	1.20[b]	≤1.20	**1.00**
	Envelope air leakage	[m³/hm$_{env}$²]	1.64[c]	≤1.64	**1.00**	3.21[b]	≤3.21	**1.00**
Alt. 2 "Other" indicators	*U-value for walls*	[W/m²K]	0.170[b]	≤0.180	**0.94**	0.130[b]	≤0.180	**0.72**
	U-value for roof	[W/m²K]	0.060[b]	≤0.130	**0.46**	0.080[b]	≤0.130	**0.62**
	U-value for floor	[W/m²K]	0.100[b]	≤0.100	**1.00**	0.170[b]	≤0.100	**1.70**
	U-value for windows/doors	[W/m²K]	1.20[b]	≤0.800	**1.50**	1.20[b]	≤0.800	**1.50**
	Window area/heated floor area	[%]	16.5	≤ 25	**0.66**	16.2	≤ 25	**0.65**
	Thermal bridges	[W/(m²K)]	0.039	≤ 0.050	**0.76**	0.039	≤ 0.07	**0.56**
	Envelope air leakage	[m³/hm$_{env}$²]	1.64[c]	≤0.656	**2.50**	3.21	≤1.28	**2.51**
	Ventilation heat recovery temperature efficiency	[%]	80.0[b]	≥80.0	**1.00**	80.0[b]	≥80.0	**1.00**
	Heat loss [d]	[W/K]	159	≤ 151[e]	**1.05**	822	≤ 687[e]	**1.20**
	Specific fan power	[kW/(m³/s)]	2.00	≤ 1.50	**1.33**	2.00	≤ 1.50	**1.33**

[a] Energy for space heating, facility appliances, domestic hot water, and household appliances.
[b] The design value.
[c] Assumed as the maximum permissible envelope air leakage according to the building code.
[d] Not an explicit criterion in the building code. However, evaluation alternative 2 allows for deviations from specific criteria related to the building envelope heat loss (U-values, thermal bridges, envelope air leakage, and ventilation heat recovery efficiency), see section 2.2.
[e] Calculated for the case study buildings based on the criteria related to the building envelope heat loss in evaluation alternative 2.

Table 9
Results for the buildings and its compliance with the energy performance criteria in the Swedish building code.

		Unit	Single-family building			Multi-family building		
			Result	Requirement	Ratio	Result	Requirement	Ratio
Energy use indicator	*Specific primary energy* [a]	[kWh/ m²year]						
	Heat pump scenario		30.9	≤90.0	**0.34**	31.4	≤85.0	**0.37**
	Peller boiler scenario		77.9	≤90.0	**0.87**	67.7	≤85.0	**0.80**
	Electric heater scenario		94.9	≤90.0	**1.05**	83.4	≤85.0	**0.98**
	District heating scenario		64.6	≤90.0	**0.72**	56.5	≤85.0	**0.67**
"Other" indicators	*Envelope U-value* [b]	[W/m²K]	0.224	≤0.400	**0.56**	0.307	≤0.400	**0.77**
	Installed electric power [c]	[kW]						
	Heat pump scenario		1.74	≤7.58	**0.23**	9.30	≤47.3	**0.20**
	Peller boiler scenario		0.21	≤7.58	**0.03**	-	≤47.3	**-**
	Electric heater scenario		8.12	≤7.58	**1.07**	41.6	≤47.3	**0.88**
	District heating scenario		0.21	≤7.58	**0.03**	-	≤47.3	**-**

[a] Energy for space heating and cooling, facility electricity, and domestic hot water
[b] For all studied heating scenarios
[c] Electric power demand for space heating and domestic hot water preparation required at DVUT. The multi-family building does not use any electricity for space heating or domestic hot water in the pellet boiler and district heating scenarios

Table 10
Evaluation results for the buildings and its compliance with the energy performance criteria in the Russian building code.

		Unit	Single-family building			Multi-family building		
			Result	Requirement	Ratio	Result	Requirement	Ratio
"Other" indicators	*U-value for walls*	[W/m²K]	0.170 [a]	≤0.328[b]	**0.52**	0.130 [a]	≤0.328 [b]	**0.40**
	U-value for roof	[W/m²K]	0.060 [a]	≤0.219[b]	**0.27**	0.080 [a]	≤0.219 [b]	**0.37**
	U-value for floor	[W/m²K]	0.100 [a]	≤0.249[b]	**0.40**	0.170 [a]	≤0.249 [b]	**0.68**
	U-value for windows/doors	[W/m²K]	1.20 [a]	≤1.99[b]	**0.60**	1. 20 [a]	≤1.99 [b]	**0.60**
	Envelope U-value multiplied by form factor[a,c]	[W/m³K]	0.205	≤ 0.461	**0.45**	0.143	≤ 0.261	**0.55**

[a] The design value
[b] Converted from m2K/W
[c] Heat loss through transmission, ventilation, and air leakage

Table 11
Building code compliance with the energy performance criteria, where "√" denotes compliance, "-" non-compliance, and "NA" not applicable.

		2017 Finnish code	2017 Norwegiancode	2019 Swedish code	2012 Russian code
Criteria on energy use indicators	Single-family building	√[a]	√	√[a]	NA
	Multi-family building	√[a]	√	√	NA
Criteria on "Other" indicators	Single-family building	–	√	√ [a]	√
	Multi-family building	–	√	√	√

[a] The building did not comply when heated by electric heater

Table 12
The maximum variation in the "result-to-requirement" ratio, in percentage points (pp) and kWh for the energy use indicators in the building codes when evaluated using the three different $NS_{id.}$

Type of building	Finland 2017		Norway 2017		Sweden 2019	
	Specific primary energy [a]		Specific net energy		Specific primary energy [a]	
	[pp]	[kWh/ m²year]	[pp]	[kWh/ m²year]	[pp]	[kWh/ m²year]
Single-family building	11.3	12.0	17.4	18.8	25.2	22.7
Multi-family building	10.3	9.2	12.3	11.7	17.0	14.4

[a] Calculated average for the four heating scenarios

4.2. Norway

Both buildings complied with the Norwegian building code when evaluatied using alternative 1. The "result-to-requirement" ratio for the single-family building and multi-family building for the *specific net energy* criteria was 89 % and 96 %, respectively. This is higher than for the Finnish and Swedish *specific primary energy* criteria in all heating scenarios except when the buildings are heated by an electric heater. The most stringent requirement in the Norwegian building code was found to be on U-*value for windows/door*, with a 100 % "result-to-requirement" ratio. Both buildings exceeded a few criteria when alternative 2 was used for the evaluation (Table 8). When evaluated as per alternative 2, the *heat loss* was found to over shoot the requirement by 5 %, and 20 % for single-family and multi-family buildings, respectively. Further, the *specific fan power* was found to exceed the requirement by 33 % as per alternative 2. The criteria in alternative 2 was found to be more stringent than the criteria in alternative 1 in the Norwegian building code. Accordingly, the criteria in alternative 1 would be the minimum energy requirement for a building to comply with the Norwegian building code, and was used in the comparisons of the building codes.

4.3. Sweden

The Swedish *specific primary energy* criterion was evaluated to a lower "result-to-requirement" ratio than the specific energy use criteria in the other building codes for both buildings when heated by heat pump or district heating and additionally for the multi-family building when it was heated by a pellet boiler (Table 9). The criteria on *envelope U-value* and *electric powerdemand* were also found to have low "result-to-requirement" ratios in these heat supply scenarios compared to the criteria in the Norwegian and Finnish building code. Accordingly, for buildings heated by these heating systems, the energy performance criteria in the Swedish building code can be inferred to be lenient as compared to the Finnish and Norwegian building codes. The Swedish energy use criteria was found to be especially lenient for buildings heated by heat pump. For example, even if the *specific primary energy* criterion in the building code is lowered by 50 % (from 90 to 45 kWh/m² and from 85 to 42.5 kWh/m² for the single and multi-family building, respectively), the buildings would still be able to meet the requirement when heated by the heat pump. This is partially due to the high COP-factor of the studied heat pump, but also due to the lenient requirement limit. A weighting factor of 1.6 is used to calculate the specific primary energy use for space heating and hot water when heated by electricity. The buildings heated by heat pumps with high COP factors use only a small quantity of electricity and accordingly the weighing factor will have only a marginal influence on the primary energy use.

When heated by electricity, the single-family building exceeded the maximum allowed *electric power demand* by 7 % and the *specific primary energy use* by 5 %. This is high compared to the "result-to-requirement" ratios for all criteria in the Norwegian and Russian building codes. Thus, next to the Finnish building code, the Swedish building code was indicated to be strict for single-family buildings when heated by electric heaters.

Compliance with the *specific primary energy* criterion in the Swedish building code should be evaluated through measurements, as opposed to the building codes in Finland and Norway where calculation-based evaluations are used for the specific energy use indicators. The measurements may be normalized according to climate and user behavior, but any changes and/or flaws in the finished building (construction, installations, and operation) could result in a higher energy use than design calculations. Thus, buildings may be designed with a safety margin to ensure compliance with the energy use criteria verified by measurements. Accordingly, the Swedish *specific primary energy* criterion in practice may be more difficult to comply with than indicated by this study.

4.4. Russia

Both buildings complied with the 2012 Russian building code. Further, the buildings were found to have lower "result-to-requirement" ratios for most of the criteria in the Russian building code as compared to the criteria in the other building codes. Hence, the energy performance criteria in the 2012 Russian building code were indicated to be lenient compared to the other three building codes. The energy performance criteria in the 2012 Russian building code have received some critique for not increasing the requirements on building energy performance as compared to the 2003 national building code [57].

4.5. Influence of the NS_{id} on the specific energy use indicators

The national standard input data (NS_{id}) used in the evaluation of the energy use indicators could influence the simulation results and affect the "result-to-requirement" ratios. To study the effect of the NS_{id} on the results of the energy use indicators, simulations were carried out by interchanging the national standard input data for Finland, Norway, and Sweden. For example, the NS_{id} of Norway was used to stimulate the specific primary energy use of the buildings as per the Finnish and Swedish building codes. Accordingly, six additional simulations for each case study building (2 for each building code) were carried out. Table 12 provides the maximum variation in the results, when the NS_{id} was varied, for the energy use indicators. For example, the Swedish *specific primary energy* was increased by 19.4 kWh/m^{2}year for the single-family building when the Finnish NS_{id} was used, while it decreased by 3.3 kWh/m^{2}year when the Norwegian NS_{id} was used. Thus, when the NS_{id}-was changed , the maximum variation for the Swedish *specific primary energy* indicator for single-family building was 22.7 kWh/m^{2}year. This corresponds to approximately 25 percentage points (pp) variation in the "result-to-requirement" ratio. Similarly, for the single-family building the maximum variation in the "result-to-requirement" ratio for the Finnish *specific primary energy* indicator and Norwegian *net energy* indicator was 11 pp and 17 pp, respectively. This suggest that the national standard input data has a large influence on a building's compliance with the specific energy use criterion.

5. Conclusions

A comparative evaluation was made of the energy performance criteria in the latest national building codes in Finland, Norway, Sweden, and Russia. The study was based on simulation of an existing single-family and a multi-family building in Sweden. Except when heated by electric heater, the residential buildings built almost a decade back in Sweden were found to meet the specific energy use requirements in the latest Swedish and Finnish building code. Similarly, the buildings were able to meet the requirement in the latest Norwegian building code (when evaluated by alternative 1) in all heat supply scenarios. This suggests a possibility to consider incorporating more stringent requirements on the energy use in these building codes. The buildings were able to meet all energy performance criteria in the Russian building code easily. For example, "the result-to-requirement" ratio for U-values of the walls for single-family and multi-family buildings was 0.52 and 0.4, respectively. The findings suggest a potential for more stringent energy performance criteria in the Russian building code. Swedish and Finnish building codes have relatively tough requirements for using electricity heating and relatively lenient requirements for heating by heat pumps. For example, when heated by electricity, the single-family building exceeded the energy use requirement of the Finnish and Swedish building code by 23 % and 5 %, respectively. However when heated by heat pumpthe building had a margin to the requirement of 43 % and 66 % for Finnish and Swedish building code, respectively.. Hence, new buildings in Finland and Sweden are less likely to use electricity for heating and more likely to use heat pumps. The buildings did not meet the Finnish criteria on *heat loss* and complied with the Norwegian criteria on *U-value for windows/doors* with no margin. Accordingly, the Finnish and Norwegian building code have relatively stringent requirements on the energy performance of the building envelope. The national standard input data was found to affect the "result-to-requirement" ratio of energy use indicator by 10 – 25 percentage points. This suggests that the national standard input has an important influence on a building's compliance with specific energy use criteria. Thus, the standard input data are an important aspect in energy use criteria that may require more attention in research and regulations. To produce comparable evaluation results, the standard input data for climate, building operation, and occupant behaviour (used in calculations or to normalize measured data) needs to be provided in detail in the building codes. Since the standard input data has a large influence on compliance evaluations of energy use criteria, legislators also need to take the specified national standard input data into account when setting the requirement limits on these indicators. For example, if the occupant behaviour and building operation represented by the standard input data is energy efficient, then the energy use criterion in the building code should be made more stringent in order to enhance the energy performance of the building. The studied building codes included indicators on the U-values and heat losses of the building envelope. At least one criterion for these "other" indicators was more stringent than the energy use criteria in each of the Finnish, Norwegian, and Swedish building codes. This indicates that "other" indicators than the energy use indicator play an important role in regulating building energy performance in the studied countries. This study was limited to a typical single and multi-family building built to modern building standards in Sweden. Future studies may include other building typologies, which may reveal additional differences between the energy performance criteria in the studied building codes.

Author contributions

Ingrid Allard together with Thomas Olofsson and Gireesh Nair conceived the study; Ingrid Allard developed the method and carried out the simulations and data analysis. Ingrid Allard and Gireesh Nair wrote the paper with feedback from Thomas Olofsson.

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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