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Multifamily building energy retrofit comparison between the United States and Finland

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Abstract:	Due to the high heating demand, energy savings in residential buildings in cold climates has played an important role in reducing carbon emissions. The study aims to investigate differences between the United States and Finland regarding characteristics and energy retrofit practices of current multifamily buildings (MFBs). The study focuses on net zero energy or nearly zero energy performance in cold and very cold climatic conditions. This paper first presents an overview of the status of multifamily housing stocks in the two countries, followed by an explanation of energy use patterns of residential buildings in both countries. Then, building codes related to energy efficiency in Finland and the United States are examined as well as major differences among the codes. Lastly, to further understand the different strategies and techniques used in energy retrofit projects, a dataset of 57 MFBs from both countries, both net zero energy buildings (ZEB) and nearly zero energy buildings (nZEB), were collected and analyzed. The preliminary results indicate three differences: (1) For the existing MFB stock, the United States has a higher average energy use, at 266 kWh/m2 (cold and very cold regions), compared to that of Finland, at 235 kWh/m2. (2) Finland has more stringent energy code requirements that contribute to lower energy use in similar cold climate conditions. (3) In Finland, the heating and ventilation systems play a more critical role in explaining the building energy use differences, while in the U.S. projects, building envelope thermal properties were found to be more influential in explaining the energy use intensity variations. (4) The actual average energy use intensity in the U.S. retrofit case buildings is 1.7 times higher than that in Finland. Four technical and regulatory factors appear to contribute to the difference in energy use intensity in the two countries. The discussion and conclusion are drawn upon those findings.
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Dear Editors:

Energy and Building

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Please find the enclosed manuscript entitled: " Multifamily building energy retrofit comparison between the United States and Finland", we are submitting for the Journal of Energy and Building.

This paper first presents an overview of the status of multifamily housing stocks in the two countries, followed by an explanation of energy use patterns of residential buildings in both countries. Then, building codes related to energy efficiency in Finland and the United States are examined as well as major differences among the codes. Lastly, to further understand the different strategies and techniques used in energy retrofit projects, a dataset of 57 MFBs from both countries, both net zero energy buildings (ZEB) and nearly zero energy buildings (nZEB), were collected and analyzed.

As such this paper should be of interest to a broad readership including those interested net zero research and practice. Thank you for your consideration of our submission! Please address all correspondence concerning this manuscript to me and feel free to correspond with me by e-mail (mhu2008@umd.edu).

Sincerely,

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Highlights

- In Finland, the heating and ventilation systems play a more critical role.
- Finland has more stringent energy code requirements than U.S.
- The actual average energy use intensity in the U.S. retrofit case buildings is 1.7 times higher than that in Finland
- Four technical and regulatory factors appear to contribute to the difference in energy use intensity

Multifamily building energy retrofit comparison between the United States and Finland

Due to the high heating demand, energy savings in residential buildings in cold climates has played an important role in reducing carbon emissions. The study aims to investigate differences between the United States and Finland regarding characteristics and energy retrofit practices of current multifamily buildings (MFBs). The study focuses on net zero energy or nearly zero energy performance in cold and very cold climatic conditions. This paper first presents an overview of the status of multifamily housing stocks in the two countries, followed by an explanation of energy use patterns of residential buildings in both countries. Then, building codes related to energy efficiency in Finland and the United States are examined as well as major differences among the codes. Lastly, to further understand the different strategies and techniques used in energy retrofit projects, a dataset of 57 MFBs from both countries, both net zero energy buildings (ZEB) and nearly zero energy buildings (nZEB), were collected and analyzed. The preliminary results indicate three differences: (1) For the existing MFB stock, the United States has a higher average energy use, at 266 kWh/m^2 (cold and very cold regions), compared to that of Finland, at 235 kWh/m^2. (2) Finland has more stringent energy code requirements that contribute to lower energy use in similar cold climate conditions. (3) In Finland, the heating and ventilation systems play a more critical role in explaining the building energy use differences, while in the U.S. projects, building envelope thermal properties were found to be more influential in explaining the energy use intensity variations. (4) The actual average energy use intensity in the U.S. retrofit case buildings is 1.7 times higher than that in Finland. Four technical and regulatory factors appear to contribute to the difference in energy use intensity in the two countries. The discussion and conclusion are drawn upon those findings.

1.0 Background

Since 2002, EU member states have been following and implementing the EU's Energy Performance of Buildings Directive [1] to achieve greater energy efficiency and reduced carbon emissions through nZEB for new buildings beginning in 2020. nZEB retrofits are required by 2050 for all member states, and each EU member state must establish its own long-term retrofit strategies to achieve the goal [2]. In the European Union, nZEBs are defined as "buildings with very high energy-efficiency, and the remaining energy demand for those highly efficient buildings is largely met through renewable energy supply, including the energy generated on the building site or nearby" [3]. In the United States, there is no country-wide mandate for ZEBs or nZEBs, although some states are more advanced than others. For example, the state of California published the Energy Efficiency Standards for Residential and Nonresidential Buildings (Title 24) with the requirements that all new residential construction will be zero net energy by 2020, all new commercial construction will be zero net energy by 2030, 50% of commercial buildings will be retrofit to ZEBs by 2030, and 50% of new major renovations of state buildings will be ZEBs by 2025 [4]. In the United States, ZEBs are described as buildings that combine energy efficiency and renewable energy generation to consume only as much energy as can be produced onsite through renewable resources over a certain period [5].

The building code requirements and practical techniques of ZEBs or nZEBs have been previously studied in the United States [6], Denmark [7], Norway [8], Sweden [9], and Finland [10]. The most effective way to reduce building energy use and related carbon emissions is to improve the energy efficiency of existing buildings [11]. Indeed, compared to constructing new buildings with higher energy performance, upgrading the existing building stock has more significant energy saving potential [12], given the millions of energy-inefficient infrastructures that already exist. Therefore, this research specifically focuses on retrofitted multifamily nZEBs and ZEBs.

Finland was selected for a comparison with the United States for two reasons. First, in Finland, the energy consumption per capita is the second highest among EU countries due to its cold climate and energy-intensive industries [13]. Second, Finland is regarded as one of the top three most progressive countries in terms of energy efficiency policies in the EU and has been leading efforts in energy use and carbon emission reductions [14]. In Finland, buildings use around 38% of total energy and contribute to 32% of the country's total CO_2 emissions (Statistics Finland 2016). At the end of 2020, there were 1,319,000 residential buildings—including attached houses, detached houses, and MFBs (apartments)—and **47%** of them were MFBs [15]. By the end of 2015, the United States had 118,200,000 residential buildings, and **12%** of them were MFBs. By the end of 2020, residential buildings in the United States accounted for around 22% of total energy use [16]. The total number of residential buildings in cold and very cold climates in the United States is around 6,600,000, which accounts for **36**% of total multifamily housing [17]. In the United States, cold and very cold climate regions are defined using heating degree days (HDD), average temperature, and precipitation data [18 19]. This method was first defined in the Residential Energy Use Survey conducted in 2015, which is administered by the U.S. Energy Information Administration (EIA).

In this study, due to the similarities in climate condition and commonalities of building characteristics, we compared multifamily retrofitted buildings in Finland with those in cold and very cold climate regions in the U.S. The first commonality is an aging infrastructure. As illustrated in Figure 1, 54% of Finnish buildings were built before 1980, many built without specific energy performance criteria as there were no building energy regulations in Finland prior to 1976 [20]. Compared to Finland, the MFBs in the U.S. are even older: 61.5% of buildings nationwide were built before 1980. The first U.S. building energy regulations (ASHRAE 90.1) were published in 1975 (ASHRAE) [21].

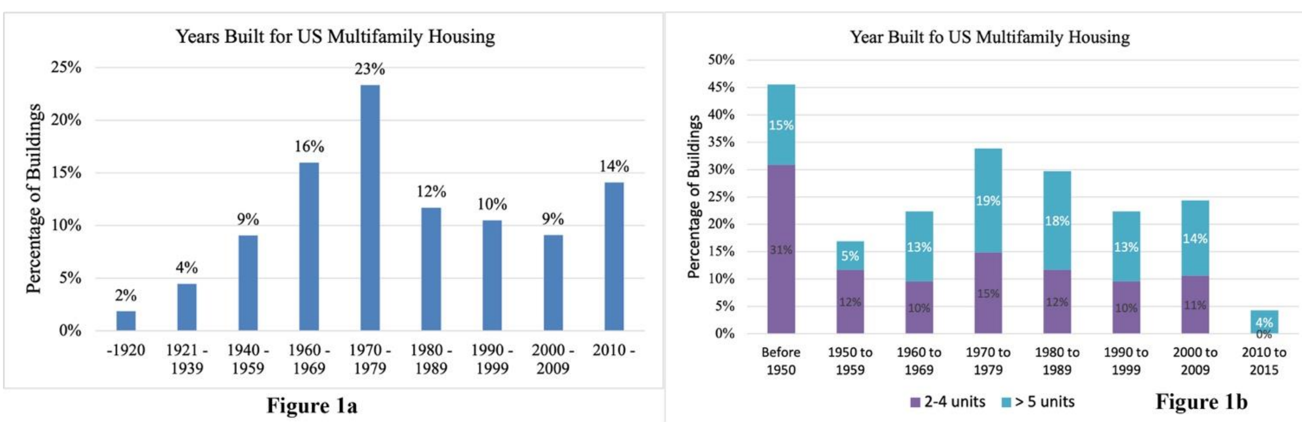

Figure 1 Percentages of multifamily housing built each decade in Finland and the U.S.

The second commonality between the two countries is the building construction type and buildings' physical characters: typical Finnish MFBs are low-rise to mid-rise buildings; 70% of the buildings are larger with three to nine stories, and the remaining 29% of buildings are smaller with one to two stories [15]. In the U.S., the ratio is similar; large MFBs account for 68% (≥5 units) and small MFBs make up the rest 32% (two to four units.) In addition, a large proportion (40%)

of U.S. MFBs are made of brick [15], while most Finnish apartment buildings are built using concrete elements [22].

Given that a large proportion of MFBs in the United States and in Finland are more than 30 years old, they require renovation and upgrades soon. In addition, these older buildings were built prior to building energy efficiency regulations being initiated. Therefore, these existing MFBs represent a great potential for energy savings and a carbon emissions reduction. A better understanding of what renovation techniques are more effective can provide insights and direction for future renovations. This study was conducted as part of the Net Zero Retrofit Development in the United States and Nordic countries (UN-NERD) research project, which investigates zero energy MFB retrofitting in the United States and Nordic countries with a focus on Finland. The overall aims of the UN-NERD project are to determine (1) how an exemplary Finnish ZEB compares to one in the U.S.; (2) the differences in influential factors on energy retrofits; (3) whether there is a major technical difference in building energy retrofits in the two countries; and (4) whether there is a cost difference. This paper focuses on the first three questions by establishing and analyzing a database of completed net zero energy MFB retrofit projects in the United States and Finland.

2.0 Materials and Method

As illustrated in Figure 2, the research was composed of three steps. In step one, housing statistical data from each country was investigated to understand the typical MFB's physical characteristics and energy use status. In the second step, the research team reached out to a variety of resources to collect data for built and verified multifamily ZEBs or nZEBs in the U.S. and Finland for a comparative study. The data collection mainly focused on two categories: building envelope thermal properties and heating/ventilation systems. The last step was analysis by multivariable regression models to understand the association between building envelope properties and heating/ventilation system variables with primary energy use outcomes. The subsequent discussion was focused on the findings from the statistical analysis and case studies. Finally, conclusions were drawn and suggestions made regarding lessons learned from the two countries. Each step is described in more detail further below.

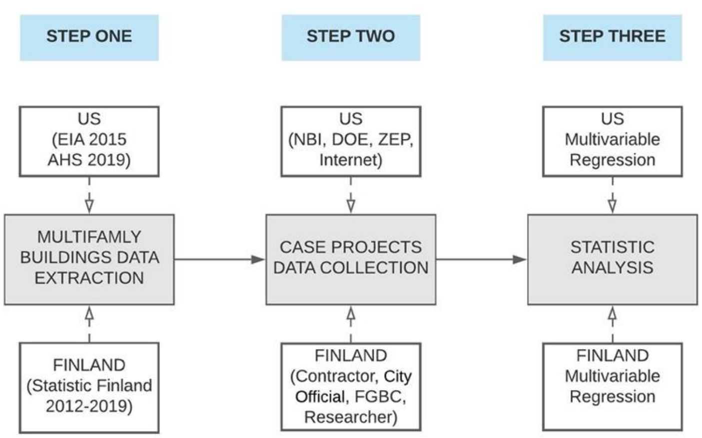

Figure 2 Research method and steps

2.1 Multifamily building data acquisition

U.S. MFB character data were downloaded from two resources: the Residential Energy Consumption Survey 2015 [18] database managed by the EIA and the American Housing Survey 2019 database managed by the U.S. Census Bureau. The energy use data were downloaded from RECS 2015, which includes around 10.6 million residential buildings in the cold and very cold climate regions. The Finnish MFB character data and energy use data were downloaded from the Statistics Finland database, which includes close to 1.4 million residential buildings.

2.2 Case project data collection

The research focused on retrofit case studies, and all the collected data were from completed retrofit projects. In the United States, the largest nZEB database is the online library created and managed by the New Buildings Institute (NBI). By the end of 2020, the NBI database contained five built and verified retrofit MFBs. Among the five verified zero energy MFBs, four are located in cold and very cold climate regions, thus we included those four case studies in our comparison. In addition, two other references were investigated: the Zero Energy Project [1] and DOE Zero Energy Ready Home program[2], leading to inclusion of another six case projects located in cold and very cold climates. Altogether, 10 built and verified zero energy or nearly zero energy MFBs were included in the U.S. data sample, representing 273 individual dwelling units from the U.S. databases. Then, detailed case studies were conducted for the 10 projects, and more technical information was extracted from online sources for further statistical analysis.

For the Finnish cases, the research team reached out to VTT Technical Research Centre of Finland (VTT)[3] and City of Tampere officials; eight built multifamily nZEBs were identified. The research team also reached out to construction companies, academic researchers, the Finish Green Building Council, and the Finnish Association of Civil Engineers. Detailed data were obtained for one MFB. In addition, the research team conducted a literature review, which yielded two published articles [[23 24]] that included the data collection of another 38 buildings. Altogether, 47 built and verified net zero or nearly net zero energy MFBs, including around 749 dwelling units, were included for Finland.

2.3 Statistical analysis

Two separate multivariable regression models (for each country) were created for building envelope components and heating/ventilation system variables (see Eq. 1–2), for the U.S. and Finland to understand the correlation between the technical factors of retrofit projects and energy use intensity after retrofit in each country. Then the fitness of the regression model was compared within the database using the likelihood ratio test to determine the power of the models. Equation 1 focuses on building envelope variables, and Equation 2 focuses on building heating and ventilation system variables.

For U.S. and Finnish building envelope variables:

$$Y_i = \beta_0 + \beta_1 (wall) + \beta_2 (roof) + \beta_3 (floor) + \beta_4 (window) + \mu_i \qquad \text{Eq.1}$$

For U.S. and Finnish heating and ventilation system variables:

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[1] The Zero Energy Project is a non-profit educational organization whose mission is to provide information on ZEBS to promote the adoption of net zero building practices in the housing market.
[2] https://www.energy.gov/eere/buildings/housing-innovation-awards
[3] VTT is a state-owned and controlled non-profit limited liability company.

$$Y_i = \beta_0 + \beta_1 (source) + \beta_2 (system) + + \beta_3 (heat\ recovery) + \mu_i \qquad \text{Eq.2}$$

Where Y_i is the primary energy use (per building); μ_i is the random effect of intercept for case i.

3.0 Findings

3.1 Existing MFB stock comparisons

In Finland, multifamily apartment buildings account for 21% of total floor area of all buildings [25] and are responsible for 17% of the total heating energy use and 26% of carbon emissions [26]. In the U.S., multifamily apartment buildings count for 12% of the total floor area and are responsible for 10% of the energy use in the residential sector [27]. In Finland, the average size of a unit in a multifamily apartment building is 53.6 m^2 with an average [28] 1.6 persons per household [29]. The average energy use for space heating alone is around 150–170 kWh/m^2 (Paiho et al. 2015)[30], and heating accounts for nearly 68% of total energy use in residential buildings [31]. Therefore, the total average energy consumption in Finnish residential buildings is estimated at around 235 kWh/m^2. In the U.S., the average size of a comparable unit is significantly larger, at 78.87 m^2 and an average of 2.1 persons per household [32]. The average residential building energy consumption in cold and very cold climate regions in the U.S. is 266 kWh/m^2 [33].

Overall, as illustrated in Figure 3, there are five major differences for energy use breakdowns between the two countries. *First*, space heating is the dominant energy end use category (68%) in Finland, while space heating accounts for less than 30% for U.S. residential buildings. The cooling load in Finland is negligible, while the cooling load in the U.S. is 11.8%, even in cold and very cold climates. *Second*, lighting energy use in the U.S. is more than three times higher than that in Finland (7.2% vs 2%). *Third*, some major appliances used in the two countries are different. For example, dishwashers and tumble dryers are common appliances in the U.S.; together, with washing machines, they account for 5% of the total energy use. However, the tumble dryer is not common in a typical Finnish household. Instead, a sauna room in a single-family house and shared sauna facilities in apartment buildings are common amenities in Finland. At the end of 2020, there were 1,319,000 residential buildings and around 1,720,000 saunas in Finland [34]. Sauna heating accounts for 5% of total energy use. The *fourth* major difference is other appliance plug loads: in addition to computers and televisions, another 20.8% of energy use is unclassified (identified as “other”) in American households, which includes the use of small devices and small kitchen appliances as well as the energy consumption from end uses not captured in the RECS household survey [35], hence these are defined as unclassified plug loads. In Finland, all other plug loads (i.e., other electrical equipment) account for 9% of energy use, which is much lower than that in the U.S. The *fifth* major difference is related to energy provision sources in residential buildings. In the U.S., natural gas and electricity are used equally, at 42%, as energy sources in residential buildings [15]. In Finland, the energy sources are electricity (34.5%), district heating (28.5%), and wood (22.2%), while gas accounts for less than 5% of the energy sources [36]. Moreover, Finland has a much higher percentage (43%) of energy generated from renewable sources [28], compared to just 11.4% in the U.S. (EIA) [37]. In summary, Finland has more clean energy sources than the U.S.

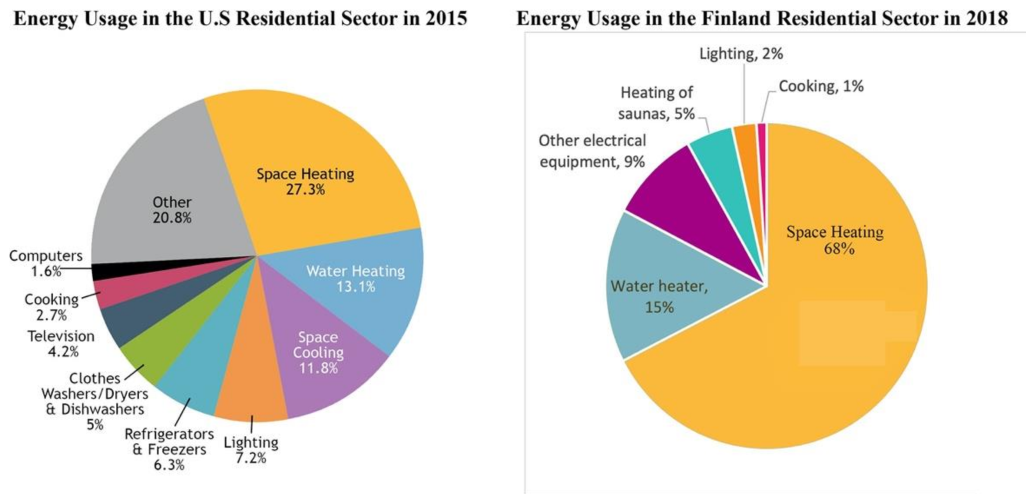

Figure 3 Energy end use breakdown (data based on Statistics Finland, EAI 2015, and the National Academies of Sciences, Engineering, and Medicine) [38]

3.2 Building energy code comparisons

This section focuses on building codes for comparable geographic regions based on climate zones.

3.2.1 Heating degree day difference

Error! Reference source not found.4 illustrates the comparable cold and very cold regions in the U.S. (in blue) that are of a similar climate to Finland. The U.S. design requirement and building code is based on HDD, a measurement used to quantify the demand for energy needed to heat buildings. The HDD is calculated by adding up the differences of the desired indoor and outdoor average temperatures, typically over a one-year period, for the purpose of building energy planning. There are different definitions and calculation methods of HDD that directly contribute to different energy consumption in the two countries [39]. After close examination, two major differences were identified in the building codes between Finland and the U.S.

Figure 4 Climate regions in the United States and Finland

The first difference is base temperature; in the U.S., HDD is calculated from TMY3 weather data with a base temperature of 18.3°C (65°F) [40]. In Finland, the base temperature is lower, at 17°C (62.6°F). Base temperatures are typically defined for a particular building as a function of the temperature that the building is heated to, and different base temperatures may reflect different typical levels of building insulation (U-values). For example, a day with a mean temperature of 4°C (40°F) has 25 HDD in the U.S. (using an 18°C base temperature), but if we use the Finnish base temperature of 17°C, then we should count fewer HDD, at 22.6. The second difference is the days included; in Finland, HDD excludes days when the average temperature is above 10°C (50°F) in the spring and above 12°C (53.6°F) in autumn (Finnish Meteorological Institute)[41]. These differences explain why in Finland there are fewer HDD than in the U.S., even though both countries are in similar climate zones. More specifically, in the U.S., the HDD value is 5,400 for a cold climate and 9,000 for a very cold climate (DOE). However, the average HDD value in Finland is 4,323, which is under half of that for the U.S.'s very cold climate average. A higher HDD value normally indicates higher energy demand for heating. The large difference in HDD values does not represent a climatic difference, but reflects the countries' different typical mean building insulation standards (U-values).

3.2.2 Building envelope code requirements

Building energy efficiency can be improved through passive design strategies that include the design of a high-performance building envelope. In recent years, passive design strategies have seen renewed interest for their energy saving potential. A building envelope is the thermal envelope that separates the indoor and outdoor environments of a building, and it includes the exterior walls, roof, floor, and fenestration (window/door). In cold climates, the most used passive building envelope design techniques are adding insulation and reducing glass heat loss [11]. The two building codes compared in this study are the U.S. ASHRAE 90.1 (2016) for climate zone 6 (very cold) and the National Building Code of Finland (by the Finnish Ministry of the Environment). Table 1 lists the basic regulatory requirements for new buildings. Finland has limited the maximum energy that can be consumed in nZEBs, while the U.S. does not have any such limit. In the U.S., there is no separate code for building retrofits; however, if the renovation area is more than 50% of the floor area, then the renovated part should meet the same standards of new construction. In Finland, there are requirements for building energy retrofits [42]. Compliance with the requirements can be verified by (1) component-specific improvements, (2) a reduction in energy consumption, or (3) an improvement in the e-value [43]. Improvements in the energy efficiency of buildings favor active means of targeting ventilation and the heating system. Compliance is thus typically verified based on options 2 or 3.

Regarding option 1, component-specific improvements, Table 1 lists the specific requirements included in the building standard or code in both countries. The allowable U-value (thermal transmittance, W/m^2K) of the thermal envelope is more than twice as high in the U.S. than in Finland, except for the mass timber wall. Higher U-values mean the thermal envelope has less resistance to heat loss. In other Nordic countries, similar thermal envelope standards have also been implemented. For example, in Norway, the most recent national building code, TEK 17, defines the maximum energy use in an MFB as 95 kWh/m^2, where the U-value is less than 0.18 W/m^2K for the exterior wall, less than 0.13 W/m^2K for roofs, less than 0.1 W/m^2K for floors, and less than 0.08 W/m^2K for windows (Norwegian Building Authority).

Table 1 Building envelope design requirements for new buildings, according to building codes (Ministry of the Environment) [44]

	Max. energy use (kWh/m^2)	Min. energy efficiency criteria (W/m^2 K)

		Wall	Mass timber wall	Roof	Floor/ slab	Window/ door/ skylight
Finland	90	0.12–0.14	0.40	0.07	0.10	0.7
U.S. (for climate zone 6, i.e., very cold climate)	No requirement	0.26	0.34	0.15	0.19	1.82

Note: Mass timber wall is not commonly used for MFBs in both countries.

3.3 Case study characteristics comparison

Table 2 and Table 3 illustrate the characteristics of the case buildings in the United States and Finland. Note that the reported energy use in both countries is measured for primary energy use, and all data reported are actual building operating energy use after renovation. There are three major differences that can be observed. First, Finnish retrofit buildings have significantly higher building envelope thermal properties (measured by lower U-values). Second, the heating source and supply system in Finland is more standardized than those used in the United States. Third, all Finnish case buildings have a heat recovery ventilation system while not all case buildings in the United States have an installed heat recovery system.

Table 2 Characteristics of case studies in the U.S. (measured energy use)

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Primary energy use (kWh/m^2)	185	74	107	132	71	95	274	221	160	157
Construction year	2006	2015	2018	2019	2015	2015	2014	2017	2015	2011
Number of units	10	7	No data	76	57	3	26	12	66	16
Number of floors	No data	3	2	4	3	4	3	3	4	3
Total gross area (m^2)	480	790	565	6224	5365	520	3510	1752	4950	1700
U-value of envelope (W/m^2K)										
External wall	0.19	0.12	0.14	0.28	0.14	0.11	0.24	0.24	0.18	0.14
Roof	0.09	0.09	0.09	0.19	0.09	0.09	0.11	0.11	0.09	0.09
Floor	0.56	0.09	0.28	0.34	0.28	0.28	0.56	0.56	0.28	0.28
Windows	1.69	1.0	1.12	1.0	0.8	0.8	1.69	1.63	1.0	0.8
Heating system										
Heat source	GSHP	ASHP	ASHP	ASHP (CO_2)	ASHP	ASHP	GAF	GSHP	SMSHP	GSHP
Heating system	Floor	DSHP	No data	Ceiling	Ceiling	No data	Ceiling	Ceiling	Floor	Floor
Supply/source	Ele	No data	Ele	No data	Ele	Ele	Gas	Ele	Ele	Ele
Ventilation system										
Type	Mech exh	No data	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh
Heat recovery efficiency	0.73	No data	0.8	0.5	0.5	0.84	none	No data	none	No data
Renewable technologies	STC, PV	No data	STC, PV	-	STC, PV	STC, PV	STC, PV	STC, PV	STC, PV	STC, PV

Table 3 Characteristics of case studies in Finland (measured energy use)

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11-47
Heating energy use (kWh/m^2)	44	40	75	87	107	61	70	63	0	59	100.7
Construction year	-	-	1961	1968	1970	1971	1974	1978	1980	1973	vary
Renovation year	2011	2011	2017	2016	2017	2017	2015	2015	2017	2017	vary
Number of units	47	44	20	78	67	70	20	42	62	91	205
Number of floors	4	5	6	7	8	8	8	8	7	7	vary
Total gross area	-	2124	1960	3693	5395	5554	2488	3024	4117	6060	3312
U-value of envelope (W/m^{2}K)											
External wall	0.08	0.08	0.22	0.22	0.4	0.4	0.22	0.29	0.22	0.085	vary
Roof	0.07	0.07	0.35	0.35	0.35	0.35	0.35	0.35	0.23	0.35	vary
Ground floor	0.1	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.1	vary
Windows	0.8	0.76	1.0	1.0	1.4	1.4	1.4	0.8	1.0	1.4	vary
Heating system											
Heat source	GSHP +DH	ASHP +DH	GSHP	DH	DH	GSHP	ASHP	DH	GSHP +DH	DH	-
Heating system	Floor	Floor	RA	RA	RA	RA	RA	RA	RA	RA	-
Ventilation											
Type	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	Mech exh	-
Heat recovery efficiency	0.73	0.73	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	-
Renewable technologies	STC, PV	STC, PV	-	-	-	-	-	-	STC, PV	PV	-

GSHP	Geothermal ground source heat pump	Mech exh	Mechanical exhaustion
ASHP	Air source heat pump	STC	Solar thermal collector
SMSHP	Single mini-split heat pump	PV	Solar electricity panel
DH	District heating	GAF	Gas furnace
RA	Radiator	Ele	Electricity from grid
DSHP	Ductless split heat pump		

3.4 Statistical analysis

3.4.1 Operational energy use

Figure 5 demonstrates the differences in building energy efficiency (after renovation) between the case buildings from the two countries. The black dots represent the average normalized energy use intensity (kWh/m^2), and the red triangle represents the national code requirement. Finland has a maximum allowed energy use intensity for nZEBs, but the U.S. does not have a requirement. The actual average (mean) energy use intensity for the U.S. database sample is on average **1.7 times** higher than that of the nZEB sample in Finland. Further, the U.S. buildings' median energy use intensity is **twice as** high as in Finland.

The size of the box in Figure 5 indicates there is a much larger variance in energy use intensity in the U.S. sample, which varies from 71 to 274 kWh/m^2, while in the Finnish sample, the variance is between 44 and 148 kWh/m^2. More U.S. buildings in the sample are within the lower energy use group, and the average U.S. building energy use is less than the median, suggesting that the majority of case projects perform well despite a few outliers (cases 7 and 8) that perform badly with much higher energy use. Those outliers are responsible for the higher median energy use intensity in U.S. case buildings. On the contrary, the Finnish projects reveal the opposite trend, where more buildings fall into the higher energy use group (higher than median), while three well-performing cases (cases 1, 2, and 9) offset the whole sample performance.

Despite the differences between the two countries, the case buildings share one similarity. The long upper whisker bar for both countries indicates that building energy use varies much among the higher energy use group, with less variance in the lower energy use group. This similarity among the lower energy use groups is a good indication that there are some **common practices and design principles** that can be extracted from those well-performing buildings and applied to future energy retrofits (refer to section 4.0 for further discussion).

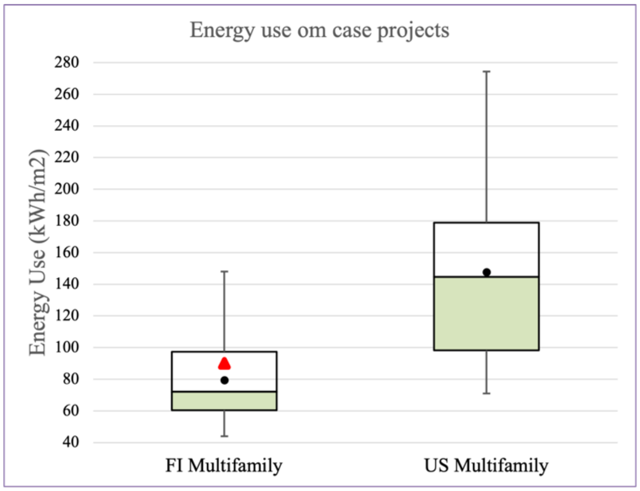

Figure 5 Box and whisker plot of case projects

3.4.2 Correlation between primary energy use intensity and the building envelope and heating and ventilation systems

Using Equation 1, we calculated the correlation between building energy use intensity and the building envelope. Table 4 shows the results. There was no statistical significance found in the Finnish case buildings, while there was significant statistical correlation in the U.S. case buildings, between the compound effect of building envelope thermal properties and building energy performance, indicated by the ANOVA F <0.05. Among the U.S. case studies, 84.6% of the buildings' primary energy use can be explained by the variables in the building envelope thermal property differences. However, there was no significant correlation between individual building envelope component variables and the varied energy use ($p>0.05$). This might be explained by the compound effect of all components being more critical than the thermal property of individual building envelope components.

Using Equation 2, we investigated the correlation between heating and ventilation systems and building energy use intensity. Table 4 shows there was no statistical significance found in the U.S. case buildings. Meanwhile, the regression model of the Finnish case buildings showed a statistical significance for the correlation between the combination of heating and ventilation systems and actual building energy performance (ANOVA F <0.05). Further, 62.7% of primary energy use intensity variability in the case buildings can be explained by the combined condition of heating and ventilation systems in Finland. Among the variables included in heating and ventilation systems, heat recovery ventilation efficiency was found to be the most influential factor ($p<0.05$) in the Finnish case buildings.

Based on the results from the regression model, a preliminary summary can be made based on the case buildings included in this study: in Finland, the heating and ventilation systems play a more critical role in explaining the building energy use differences compared to the building envelope properties, which were relatively homogenous across the Finnish sample. In addition, the efficiency of heat recovery ventilation systems is the most influential variable explaining the difference in building energy use intensity in the Finnish sample. In contrast, the overall building envelope thermal properties in the U.S. sample, which were heterogenous, were found to be more influential than the heating and ventilation systems in explaining the energy use differences**.**

Table 4 Statistical analysis of differences in primary energy use and in the building envelope and heating and ventilation systems

Regression Categories	Variables	R square	ANOVA F Significance	ANOVA F	P-value	Coefficients
U.S. Envelope	Wall	0.846	0.029	6.90	0.105	919.93
	Roof				0.137	-1227.64
	Floor				0.156	216.69
	Window				0.458	-26.06
Finnish Envelope	Wall	0.051	0.935	0.19	0.410	178.42
	Roof				0.349	0.123
	Floor				0.563	-520.32
	Window				0.756	-57.68
U.S. Heating Service	Source	0.558	0.154	2.52	0.212	-42.82
	System				0.349	17.09
	Heat recovery efficiency				0.059	-244.90
Finnish Heating Service	Source	0.627	0.032	5.87	0.351	0.083
	System				0.514	33.51
	Heat recovery efficiency				0.044	-141.18

4.0 Discussion

As illustrated in Figure 6, three categorical factors can impact energy use in buildings: physical factors, human factors, and technical and regulatory factors. The physical factors refer to building physical characteristics, such as compact ratio, building and unit size, and orientation. These physical factors are typically not modified in the energy retrofit projects. Human factors are less predictable, which may also explain the actual energy use variance, though no such data was available in this study. Technical factors refer to the technical variables that have an impact on building energy efficiency. In this study, we have focused on the building service system and building envelope thermal properties. In the building service system, we concentrate on the heating and ventilation system based on the unique cold climate condition. In a cold climate, the space heating demand is typically high, accounting for between 40% and 60% of the total energy use in buildings. Therefore, measures to reduce space heating demand and to deliver the remaining required heating efficiently are typically established in Nordic countries [39], such as increased insulation, improved triple glazed window performance (Ala-Kotila, 2020), efficient heat recovery ventilation systems (Ng & Payne 2016), and district heating systems (Paiho & Reda 2016). In this study, we focused on combined technical and regulatory factors. The reason we combined the factors is because the requirements of technical factors are often defined in building standards, codes, and national requirements and policies—and changes in regulations can have an immediate impact on building technical factors. For example, in Finland, there is a required maximum energy use intensity allowed; therefore, there is a clear energy performance target and goal for the project, hence all technical variables must work toward meeting the energy performance target. Meanwhile, a lack of requirements in the United States will put less pressure on building teams to optimize the technical design to achieve a higher energy performance goal.

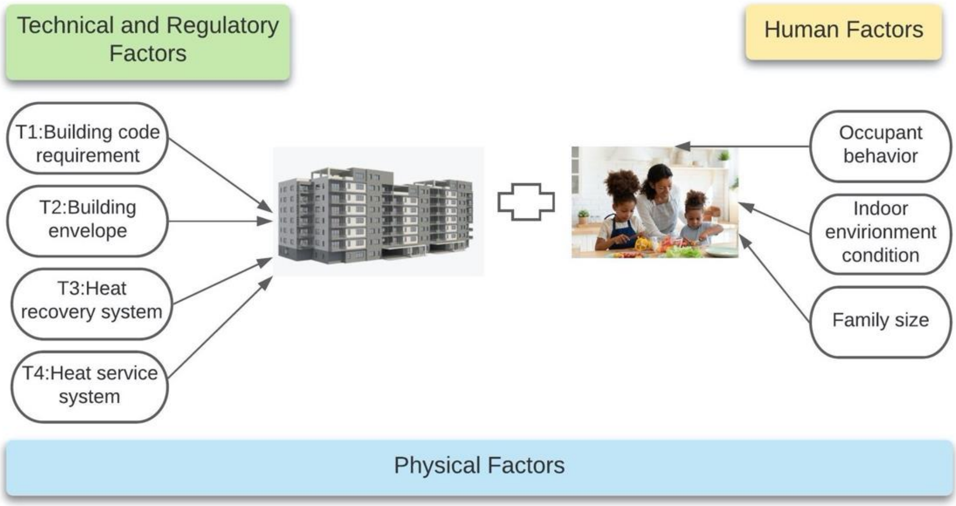

Figure 6 Influential factors that affect building energy use intensity

Four major technical/regulatory factors were found that contribute to the difference in energy use intensity (after renovation) between the U.S. and Finland case buildings. (T1) Building code requirements on maximum energy use for nZEBs: Finland has set a maximum energy use for different building types, which are reinforceable as national standards, while the U.S. has none. Although the requirements are only set for new buildings, they also influence building retrofits, both as the starting point of the building's performance pre-retrofit, as well as similar energy-efficient technologies being used in both new-build and retrofit buildings. (T2) Building code requirements on building envelope thermal properties: Finland's requirements are more stringent than those in the same climate condition in the U.S. (T3) Heat recovery ventilation systems. (T4) Heating service systems: in Finland, the use of the heat pump system was present in all studied projects, while the heat pump system is still new to the U.S. residential building sector. In addition, district heating is the dominant heating source in Finland while most U.S. buildings in a very cold climate rely on central warm-air furnaces (60%) (EIA Table H6.6). Another difference in the heat supply systems: the radiator is the most used heating supply system in Finland, whereas heat is supplied either through the floor or ceiling systems in the U.S.

Among the four findings, T1 is largely dependent on the regulatory structure. In the U.S., each state decides whether to adopt a building energy code and which version to adopt [4]. Currently, six out of seven states located in cold and very cold climates—North Dakota, South Dakota, Wyoming, Colorado, Kansas, and Missouri—have not adopted any state-wide building energy code as of the end of 2020 (DOE). Consequently, building energy codes and national policies will not be reinforceable in those states. This can potentially explain the large energy performance variance in retrofit buildings as reported in the U.S. case buildings. If there are no incentives nor penalties to perform an energy retrofit, most building owners will choose cost-effective solutions, which may not result in an energy performance efficiency increase. For T2 building envelope requirement differences, as mentioned in section 3, the retrofitted building thermal envelope explains the varying building energy use in the U.S. sample. This indicates that when upgrading an energy-inefficient building, large energy reductions can be obtained from retrofitting the building envelope to be more energy efficient.

For T3, the heat recovery ventilation system is closely related to the building envelope's thermal properties. The Finnish case buildings' exterior envelopes had extremely low U-values. The lower the U-value, the lower the heat loss through the building envelope, and the more the proportional heat loss through other heat loss paths, such as by mechanical ventilation. Therefore, any differences in heat recovery ventilation efficiency will have a bigger impact on the building's overall energy use reduction, which is represented in the regression model analysis result of the Finnish case buildings (refer to Table 4). Consequently, in the Finnish case buildings, despite the common perception of a building envelope upgrade as an effective energy use reduction method, if the building already has decent thermal properties, further advancement of the building envelope might not have a significant impact on further energy use reductions. This finding is in alignment with other studies; for example, Nord pointed out that in Nordic countries, an improvement in the building envelope does not necessarily include upgrading the entire building envelope [39]. In some cases, improvement of the roof alone may be sufficient to achieve a substantial heat demand reduction, though this depends on the existing building's baseline energy performance pre-retrofit.

For T4, in Finnish buildings, a variety of heat pump systems were used. One common system is an air-to-water exhaust heat pump, which can recover heat from exhaust air. In some renovation projects, ground source heat pumps and wastewater heat pumps were used. From a cost efficiency point of view, heat pumps are a more cost-effective intervention than adding additional insulation. However, the higher investment cost of the ground source heat pump may not be justified if air source heat pumps (air-to-water) are equally effective [45]. Hamdy's study indicated that ground source heat pumps are popular in detached single-family houses in Finland if the consideration is the primary energy use and life cycle cost [46]. In the United States, the heat pump is less common, with less than 40% of residential buildings using a heat pump system [35]. In recent years, the U.S. Department of Energy has been promoting the use of a heat pump system. However, there are limitations to the system. We used the heat pumps in Finland to demonstrate the importance of conditions when considering using a heat pump system. The majority of heat distribution systems in older Finnish homes are water-based central heating with demand temperatures of 60/8°C. However, heat pumps cannot deliver such high temperatures; instead, low temperature radiators with demand temperatures of 35–45 ^{0}C are more suitable for heat pumps and their efficient operation [47]. Therefore, combining a low service temperature heat pump system with a tight thermal envelope provides an optimized solution for cold and very cold regions. Consequently, to ensure a thermally comfortable indoor environment under a tight thermal envelope condition, building opening improvements, like new energy-efficient windows, are also needed. As we observed in the Finnish case buildings, the building envelope and heating and ventilation system retrofits were often done together to make sure the retrofit project not only resulted in an energy use reduction but also provided a good indoor environment condition.

Besides the four technical/regulatory differences, the U.S. case buildings also had wider actual energy performance variation after renovation, compared to the Finnish projects. Human factors may be critical determining factors for such differences and require further research.

5.0 Conclusion

This paper reviewed different standards and practices in the U.S. and Finland for improving the energy performance of existing residential buildings. The results found that few standards are obligatory in the U.S., while high building standards apply in Finland. This in turn is reflected in the reported energy use of a sample of residential buildings in the U.S. and Finland with the goal to become nearly zero energy or net zero energy. The comparison of the Finnish and American buildings showed that good technical practices can be learned from Finland to reduce the heating demand in cold and very cold climate regions of the United States. This includes (1) increasing building envelope thermal properties by adopting higher building energy regulation standards; (2) using a heat recovery ventilation system to recover heat from exhaust air; (3) installing a heat pump, with the main benefits of heat pump systems realized when the heating demand is low in well-insulated buildings; and (4) installing heat recovery ventilation systems.

Compared to Finland and other Nordic countries with more stringent energy consumption requirements, the United States is far behind. To date, the biggest driver for ZEBs in the United States is market demand since there are no nation-wide enforceable regulations or policies to renovate existing buildings to become net zero or nearly zero energy [48]. Therefore, learning from good practices in Nordic countries can provide timely information for policy makers and designers to make urgent and effective decisions that improve the existing building stock's energy efficiency in cold and very cold climate regions in the United States.

Limitations of the study include limited data collected for the U.S. cases and a lack of in-situ reported energy use, as well as the absence of pre-retrofit data to compare against post-retrofit performance data. Further research is needed to understand the pre- and post-performance, which may explain some of the observed variability in buildings retrofitted to similar standards in both countries, including the study of human factors (i.e., user behavior) in occupying their homes and associated impacts on energy use. Studies of the changing social, technological, and economic conditions that have shaped energy use in the past and are likely to influence energy use in the future are also needed [49], alongside the impact of a changing climate.

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Conflict of Interest

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