Energy Retrofit In Cold And Very Cold Climate Comparison

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Due to the high heating demand, energy savings in residential buildings in cold climates has played an important role in reducing carbon emissions. The goal of this study is to investigate the difference of current multifamily buildings' energy retrofit practices in the United States and Finland, with aim to achieve net zero energy or nearly net zero energy. Altogether, data of 57 net zero (ZEB) and nearly net zero energy (nZEB) multifamily buildings from both countries were collected and analyzed. The preliminary results indicate three differences: (1) for existing multifamily building stock, the United States has higher average energy use 266 kWh/m2, compared to that of Finland at 220-250 kWh/m2; (2) Finland has much more strict energy code requirements that contribute to the lower energy use in the similar climate condition; (3) in the built nZEB and ZEB projects, the average energy in United States is 1.7 times higher than in Finland.

Background

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 (EII) [1]. 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 [2]. In Finland, buildings use around 38% of total energy and contribute to 32% of the country's total CO2 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 [3]. 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 [4]. 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 [5]. In the United States, cold and very cold climate regions are defined using heating degree days (HDD), average temperature, and precipitation data [6,7]. 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 [8]. 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) [9].

Materials and Method

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.

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 the Residential Energy Consumption Survey (RECS) 2015, which includes around 10.6

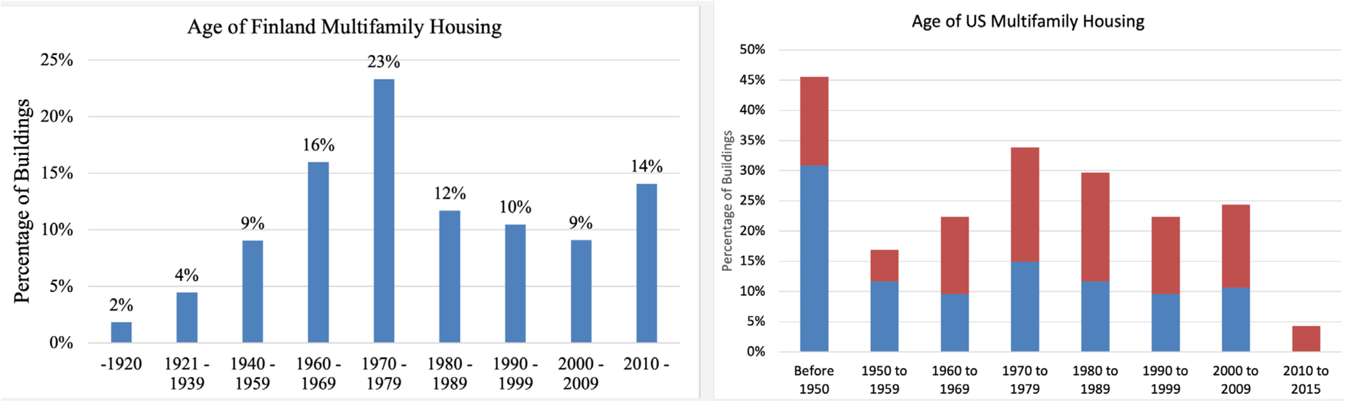


Figure 1a Finnish Buildings **Figure 1b US Buildings**

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

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 of 1.4 million residential buildings.

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 with energy use data included, 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, the Zero Energy Project and DOE Zero Energy Ready Home program were investigated, leading to the 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. The research team also reached out to Team Zero, which has a large online database including self-reported net zero energy homes (multifamily and single family) in the U.S. and Canada. In the database Team Zero shared with the research team, 12% was of existing building retrofit projects. However, despite a large number of projects listed in the database, there was no actual energy use data, no information on building envelope or building systems and were therefore not included for analysis. Hence detailed analyses were conducted for the 10 cases, 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) and City of Tampere officials; eight built multifamily nZEBs were identified. The research team also reached out to construction companies, academic researchers, the Finnish Green Building Council, and the Finnish Association of Civil Engineers. Detailed data were obtained for one additional MFB. In addition, the research team conducted a literature review, which yielded two published articles, that included the data collection of another 38 buildings. Hence. altogether, 47 built and verified net zero or nearly net zero energy MFBs, including around 749 dwelling units, were included for Finland.

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 (EUI) 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:

$$Yi = \beta 0 + \beta 1(wall) + \beta 2(roof) + \beta 3(floor) + \beta 4(window) + \mu i \qquad \text{Eq.1}$$

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

$$Yi = \beta 0 + \beta 1(source) + \beta 2(system) + \beta 3(heat\ recovery) + \mu i \qquad \text{Eq.2}$$

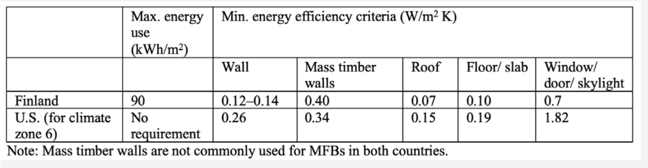
Where Yi is the primary energy use (per building); μi is the random effect of intercept for case i.

FINDINGS

Building energy code comparisons

Finland has a limit on 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 constructions. In Finland, there are requirements for building energy retrofits. 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. Improvements in the energy efficiency of buildings favour active means of targeting ventilation and the heating system. Compliance is thus typically verified based on options 2 or 3.

Regarding option 1, i.e. component-specific improvements, Table 1 lists the specific requirements included in the building standard or code in both countries. The allowable U-values (thermal transmittance, W/m2K) of the thermal envelope is more than twice as high in the U.S. than in Finland, except for mass timber walls. 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/m2, where the U-value is less than 0.18 W/m2K for the exterior wall, less than 0.13 W/m2K for roofs, less than 0.1 W/m2K for floors, and less than 0.08 W/m2K for windows (Norwegian Building Authority).



	Max. energy use (kWh/m²)	Min. energy efficiency criteria (W/m² K)				
		Wall	Mass timber walls	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)	No requirement	0.26	0.34	0.15	0.19	1.82

Note: Mass timber walls are not commonly used for MFBs in both countries.

Table 1. Building envelope design requirements for new buildings)

Operational Energy Use

Figure 2 demonstrates the differences in building energy efficiency (after renovation) between the case buildings from the two countries. The black dots represent the average normalized EUI (kWh/m2), and the red triangle represents the national code requirement. Finland has a maximum allowed EUI for nZEBs, but the U.S. does not have a requirement. The actual mean EUI (148 kWh/m2/year) for the U.S. database sample is 1.7 times higher than that of the nZEB sample in Finland (80 kWh/m2). Further, the U.S. buildings' median EUI is twice as high as in Finland.

The size of the box in Figure 2 indicates there is a much larger variance in EUI in the U.S. sample, which varies from 71 to 274 kWh/m2, while in the Finnish sample, the variance is between 44 and 148 kWh/m2. 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 EUI 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.

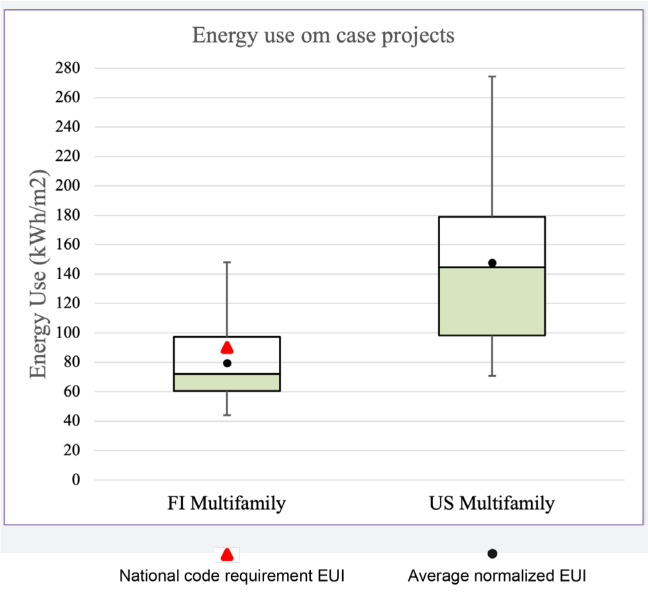
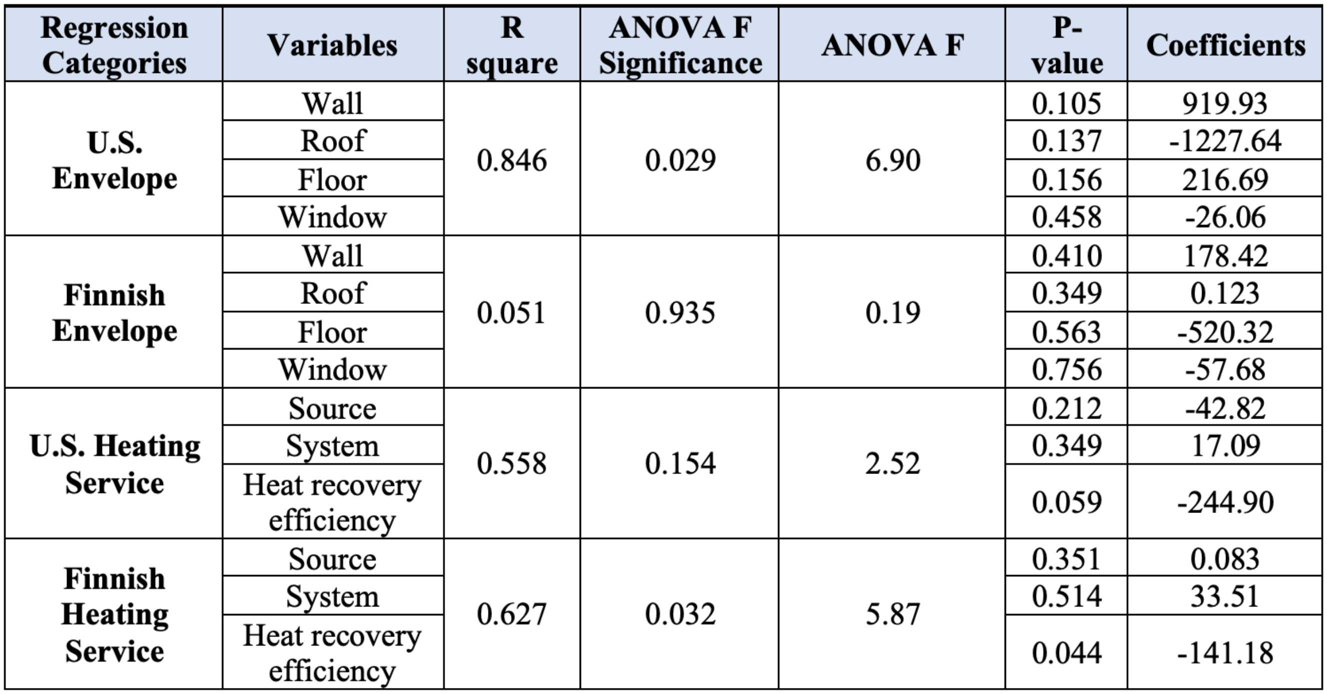


Figure 2. Box and whisker plot of case projects in both countries

Despite the differences between the two countries, the case buildings share one similarity. The long upper whisker bar for both countries indicate that building energy use varies much more among the higher energy use group, with less variance in the lower energy use groups. 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.

Correlation between primary EUI and the building envelope and heating and ventilation systems

Using Equation 1, the correlation between building EUI and the buildings' thermal envelope characteristics was calculated–see Table 2. 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



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

Table 2 Statistical analysis of differences in primary energy use and in the building envelope and heating and ventilation systems

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, the correlation between heating and ventilation system characteristics and building energy use intensity was investigated. Table 2 shows there was no statistical significance 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 EUI variability in the case buildings can be explained by the combined condition of heating and ventilation systems in Finland. Among the variables studied and included in heating and ventilation systems, heat recovery ventilation efficiency was found to be the most influential factor in the Finnish case buildings. However other factors are also likely to play a role in the variation in energy use, such as for example human behaviour, but this data was not available for the cases studied.

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 in the Finnish sample 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 EUI 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.

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. Altogether, 10 built and verified net zero or nearly net zero energy multi-family buildings (MFBs), encompassing 273 dwelling units, were studied in the U.S., with 47 MFBs in Finland, representing 749 individual dwellings were included in this study.

Findings highlighted that the Finnish zero energy retrofits have much lower reported energy use (mean 80 kWh/m2) than the energy retrofitted MFBs in the U.S (mean 184 kWh/m2). There is a much larger variance in EUI in the U.S. sample, which varies from 71 to 274 kWh/m2, while in the Finnish sample, the variance is between 44 and 148 kWh/m2. Despite the differences between the two countries, both countries indicate that building energy use varies much more among the higher energy use group, with less variance in the lower energy use groups, indicating that lessons can be learned from those well-performing buildings and applied to future energy retrofits.

Compared to Finland and other Nordic countries with more stringent energy consumption requirements, the United States is far behind. To date, there are no nation-wide enforceable regulations or policies to renovate existing buildings to become net zero or nearly zero energy [13]. Therefore, learning from good practices in Nordic countries such as Finland 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. Good technical practices can be learned from Finland to reduce the heating demand in cold and very cold climate regions of the U.S. This includes (1) improving building envelope thermal properties (i.e. low U-values) by adopting higher building energy regulation standards; (2) using efficient heat recovery ventilation systems to recover heat from exhaust air when providing background ventilation; (3) heat pump systems are optimized when the heating demand is low in well-insulated buildings and with low surface temperature heating systems.

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 [14], alongside the impact of a changing climate. This is highlighted for further research.

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