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Heating and Cooling Primary Energy Demand and CO_2 Emissions: Lithuanian A+ Buildings and/in Different European Locations

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Abstract: National legal and political regulation in the field of energy efficiency is closely connected to minimizing energy consumption in buildings. Within the framework of implementing Directive 2018/844/EU on the energy performance of buildings in Europe, the practice of its application differs from country to country. This study aims to reveal the differences in the energy indicators of an energy-efficient building in European states. To that end, an analysis was made to compare the results of a single-family home model in 11 city locations with different climatic conditions (from the Mediterranean to Nordic) and appropriate national regulations in place for the past three years. The simulation was done using IDA Indoor Climate and Energy software, EQUA Simulation AB, Stockholm, Sweden. The demand for primary energy is based on primary energy factors. A comparison of overall heat transfer coefficients for walls and windows in an energy-efficient building in different locations was made to reveal the differences in applicable national regulations. The results showcase the primary energy demand depending on the different climatic conditions for building heating and cooling purposes, as appropriate, and on CO_2 emissions. The study has shown the energy demand for cooling to increase significantly—by 65% in the case of Vilnius, whereas only a slight decrease in the demand for heating. Furthermore, a Lithuanian energy class A+ building is singled out as an individual case, its energy indicators determined for a different location under analysis.

Keywords: energy class; energy efficiency; primary energy; heating and cooling; CO_2 emissions

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1. Introduction

Modern buildings have come to be the third-largest group of consumers of fossil fuel after industry and agriculture. What is more, 30–40% of all key global resources are consumed by none other than the construction sector [1]. The building sector is considered the main and largest energy consumer on the global scale, and 40% of all primary energy (PE) generated in the US and the European Union (EU) is consumed in buildings [2,3]. With the economy growing and urban development picking up pace, one can look forward to a further increase in the building sector and a parallel surge in energy consumption, to be boosted by the accelerating climate change as well. The primary objective of this study is to assess the energy performance of energy-efficient buildings in European countries, to analyze the relationship between different climatic conditions and the building's primary energy needs, and to determine how climate change contributes to a building's energy consumption for heating and cooling.

It is a widely known fact that greenhouse gas (GHG) emissions are the number one reason behind climate change and the global warming that follows, as well as extreme weather [4]. Obviously, buildings also have a role in driving climate change: 19% of all GHG emissions occur through energy processes decarbonization in buildings [5]. It is the matter of building decarbonization that has been the focal point of attention over the past few decades, as achieving energy efficiency in buildings and switching to renewable energy has a large potential in reducing GHG emissions in the future [6].

In a bid to improve the energy performance of buildings, in 2018 the EU adopted Directive 2018/844/EU, partially amending Directive 2010/31/EU on the energy performance of buildings [7]. The latest EU directive is geared towards improving the energy efficiency of buildings, ensuring the right indoor climate, and reducing the use of fossil fuel whilst increasing the availability of renewable energy. This directive aims to contribute to the EU's goal of decarbonizing the building sector by 2050 [8]. The results of an analysis conducted by the European Commission (EC) in 2011 have shown that GHG emissions in the building sector can be cut by a staggering 90% by 2050 [9]. The EU goal of becoming a climate-neutral zone is also seeing a contribution from the building sector with nearly zero-energy buildings (NZEB), which were supposed to become the benchmark in the EU residential building market as of 2021 [7].

EU member state documents provide varying definitions of energy-efficient buildings, yet their underlying feature is defined as follows: these buildings consume little energy, and any energy consumption is done in an efficient way [10]. Some of Europe's first high-energy class buildings were introduced in German: these are the so-called passive houses and buildings bearing the Minergie seal of quality in Switzerland [1].

Following the adoption of the updated Building Energy Performance Directive [7], European countries and Member States had to amend their national legislation to include legal solutions in connection with NZEB. The main requirements for the primary energy consumption, total annual heating, and cooling demands, envelope heat transfer indicators, airtightness, and infiltration of buildings differ from one European country to another. However, these are just some of the differences that affect an effective entrenchment of NZEB in Europe.

A review by the Institute for Energy Efficiency has backed the information presented in the amendment to the European Commission regulation (Directive (EU) 2018/844) that differences in climatic conditions preclude the application of a single NZEB efficiency value suitable for all European countries [11]. Therefore, in the EU (and Norway) these buildings are covered by different national regulations and requirements, which makes a consistent increase in the availability of such buildings in different economies more difficult.

The latest review of political strategies by the Building Performance Institute Europe (BPIE) has highlighted the key differences when it comes to implementing the requirements of Directive 2018/844/EU among the EU states. According to the BPIE, (1) the timing of hands-on application of the NZEB concept varies among the states (some of the Member States have complied with the requirements for implementation ahead of time while others are lagging behind); (2) Member States use different definitions and approaches to determine national NZEB definitions; (3) approaches to calculation and performance levels to be achieved by NZEBs under construction are variegated; (4) a portion of the energy consumed to be replaced by renewable energy varies from country to country. Another important aspect is that some of the Member States had developed (and have never updated) their approaches to NZEB years before such buildings became mandatory. As a result, the national standards of these buildings are not aligned with the EU's goal of becoming a climate-neutral zone by [12].

One stipulation of Directive 2018/844/EU is the mandatory inclusion of the numerical indicator of primary energy (kWh/m^2/year) in the national plans of Member State NZEB strategies. Considering that the energy efficiency of a building is affected by different climatic conditions and the building's typology, geometry, location, engineering mechanical systems, and so on, many Member States (with the exception of Austria, Flanders, Germany, Italy, Luxembourg, and Portugal where PE values are calculated on the basis of benchmark buildings) have set a certain range of primary energy consumption [12]. In its 2016 recommendations and guidelines for ensuring the good NZEB practice in the Member States, the EC indicated the comparable limit values of primary energy differentiated by four key climatic zones: Mediterranean, Oceanic, Continental, and Nordic [13,14]. According to a report by the International Energy Agency (2018), there is a global slowdown in the progress of energy policy, indicating that the evolution of building energy codes is failing to keep up with the growth of the economies of rapidly developing countries [14]. In 2018, two-thirds of countries worldwide were short on building energy efficiency codes and legal regulations. It means that in 2018 more than three billion square meters of useful building area were built without any mandatory energy performance requirements.

1.1. Climate Change on Residential Buildings in Europe

To achieve the sustainable development scenario, all countries of the world must switch to mandatory building energy efficiency laws by the year 2030 [14]. Improvements in the energy efficiency of buildings and sustainable development of renewable energy are a must in terms of overcoming the ever-growing energy consumption and the consequences of climate change [8]. Climate change and building energy processes share a paradoxical bond: these days, the processes that take place in buildings contribute to climate change; according to a number of studies (Table 1), the consequences of climate change will drive the energy consumption for building cooling purposes up. Scientific studies conducted decades ago noted that climate change would have a direct impact on the energy and thermal properties of buildings [15,16].

Table 1. A summary of previous studies pertaining to the effect of climate change on residential buildings in Europe.

Country	Period	Climate Scenario	Conclusion	Reference
Sweden	2050–2100	RCP [1] scenario 4.5 (the radiative forcing of GHG is reduced to 4.5 W/m^2) and RCP scenario 8.5 (GHG increases, its radiative forcing going up to 8.5 W/m^2) [17]	A 13–22% drop in the demand for heating, a 33–49% increase in the demand for cooling	[18]
Finland	2030–2050–2100	Drafted on the basis of the CMIP3 global climate model [19]	A 20–40% drop in the demand for heating, a 40–80% increase in the demand for cooling	[20]
Switzerland	2100	It is assumed that the average annual air temperature will increase by 4.4 °C compared to the climatologic standards of 1961–1990	A 33–44% drop in the demand for heating (cooling is not considered)	[21]
Germany	2060	It is assumed that the average annual air temperature will increase by 1–3 °C	A 44–75% drop in the demand for heating and a 28–59% increase in the demand for cooling	[16]
Greece	2100	Three scenarios by the Intergovernmental Panel on Climate Change are used [15]	A 44–75% drop in the demand for heating and a 28–59% increase in the demand for cooling	[22]

[1] RPC—Representative Concentration Pathway.

All kinds of research have been undertaken around the globe over the past few decades in order to analyze the effect climate change has on buildings. Table 1 shows the results of simulation studies of residential buildings in Europe highlighting the impact of climate change on the energy needs of buildings.

Depending on the climatic data of different countries, climate change scenarios, and other assumptions, the summary of studies in Table 1 shows that when the building's demand for heating drops by roughly one-half, the demand for cooling may go up by a massive 80%. Isaac and van Vuuren have estimated that climate change will drive the need for heating energy by more than 30% worldwide by 2010, while the demand for cooling energy will go up by nearly 80% [23].

1.2. The Current Situation in the European Zones Covered by the Analysis

Based on the values established by the EC, countries with prevalently milder (Mediterranean) climates must ensure the lowest demand for net primary energy and the largest share of energy from renewable sources [12]. Still, considering the primary energy of a building and notwithstanding whether it is supplied from renewable sources, the range of primary energy across all four European climate zones is much narrower: the PE demands of a single-family home must fall within the recommended 50–90 kWh/m^2/year (Table 2) [13].

Table 2. European Commission standards of building performance and renewable energy resources for different climate zones [13].

Climate Zone	Demand for Net PE, kWh/m^2/year	Energy from Renewable Energy Sources, kWh/m^2/year	PE Ceiling, Including Energy from Renewable Sources, kWh/m^2/year	Renewable Energy Sources as a Percentage of Total PE
Mediterranean	0–15	50	50–65	87%
Oceanic	15–30	35	50–65	61%
Continental	20–40	30	50–70	50%
Nordic	40–65	25	65–90	32%

Based on a review by the BPIE (2021), regulations of 13 Member States point to primary energy values that fall within the limit of 50–90 kWh/m^2/year as recommended by the Commission. Denmark, Croatia, and Ireland are more stringent in their requirements, and their recommended values are below those laid down in the EC guidelines. Whereas countries such as Bulgaria, Latvia, Cyprus, Hungary, the Czech Republic, Finland, and Romania are disregarding the guideline recommendations and have set primary energy values above those recommended by the EC [12]. The differences in PE demand in European states and the gap between the national values and the EC requirement for the demand in countries covered by the analysis are shown in Figure 1.

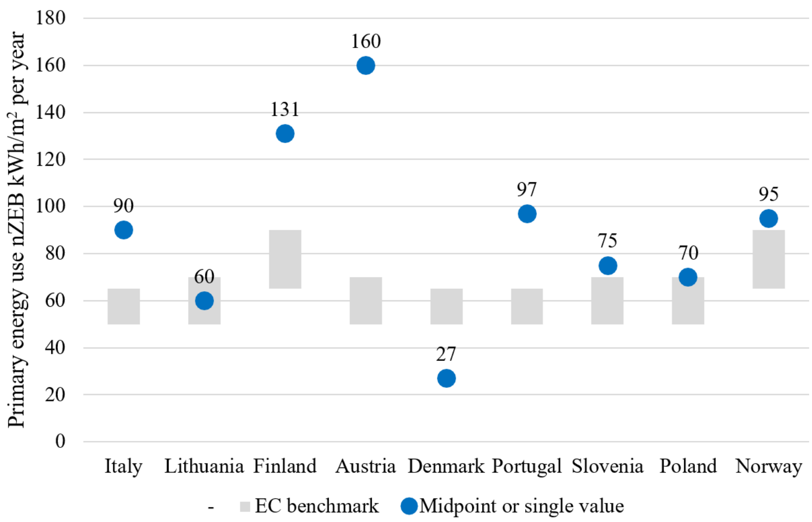

Figure 1. NZEB values (kWh/m^2/year) for single-family homes in European countries analyzed.

A more precise breakdown of the values established by the countries analyzed and those recommended by the EC are presented in Table 3.

Evidently, only Lithuania and Poland make it to the EC's brackets of primary energy demand. Denmark's national regulations stipulate a PE value that is nearly three times below the EC recommendations. For Norway (it is assumed that Norway is appraised on a par to the EU countries) and Slovenia, the PE limits are close to what the EC recommends. Therefore, the aim of this paper is to analyze and compare differences in the energy indicators of an energy-efficient building in different European states (with climate from Mediterranean to Nordic). This reveals differences in both climatic conditions and country legislation. At the same time, this contributes to the application of the NZEB concept. A single-family home is selected as a case study.

Table 3. PE values in the countries covered by the analysis and those recommended by the European Commission.

Country Analyzed	PE Value as Recommended by the EC, kWh/m^2/year [1]	Source
Italy	65	PE value determined based on an assumption (considering the results of projects completed) [24]
Lithuania	70	[25]
Finland	90	[12]
Austria	70	[26]
Denmark	65	[12]
Portugal	65	[27]
Slovenia	70	[12]
Poland	70	[12]
Norway	90	[28]

[1] Ref [13] is the source of PE value as recommended by the EC. If the subject countries provide several limit values, the average PE values are specified for the purposes of this comparison.

2. Methodology and Case Study

This case study analyses the following European countries and cities: Lithuania (Vilnius), Finland (Jyväskylä), Italy (Palermo and Bologna), Denmark (Copenhagen), Portugal (Lisbon and (Bragança), Slovenia (Ljubljana), Poland (Warsaw), Norway (Oslo), Austria (Bregenz). This choice has been driven by the desire to analyze and compare the data and results for northern and southern, as well as eastern, western, and central states alike. A comparison of the heating transfer ratios applicable to energy-efficient buildings is followed by an analysis of building energy indicators in different climatic conditions conducted on the basis of the methodology developed by Sartori et al. and D'Agostino and Parker [29,30].

The methods used in the study are presented in Figure 2. They are based on the data gathered from Guidelines on Energy System Analysis and Cost Optimality in Early Design of ZEB, a report by Sartori et al. and the methodology developed by D'Agostino and Parker designed to analyze NZEB buildings in terms of price optimization [29,30].

2.1. Study-Case Building Characteristics

The modeled building is a single-apartment, one-floor residential home with a gross useful area of 100 m^2. The home is assumed to be inhabited by a family of four. The façade of the simulated building is facing south, nearly 68% of the façade (17.60 m^2) is a panoramic window. The key data of the building's envelopes are presented in Table 4.

Table 4. Envelope areas of the modeled building.

Building Envelope	Envelope Area, m^2
Walls	72.20
Doors	1.60
Windows	30.2
Floors	100.0
Roof	100.0

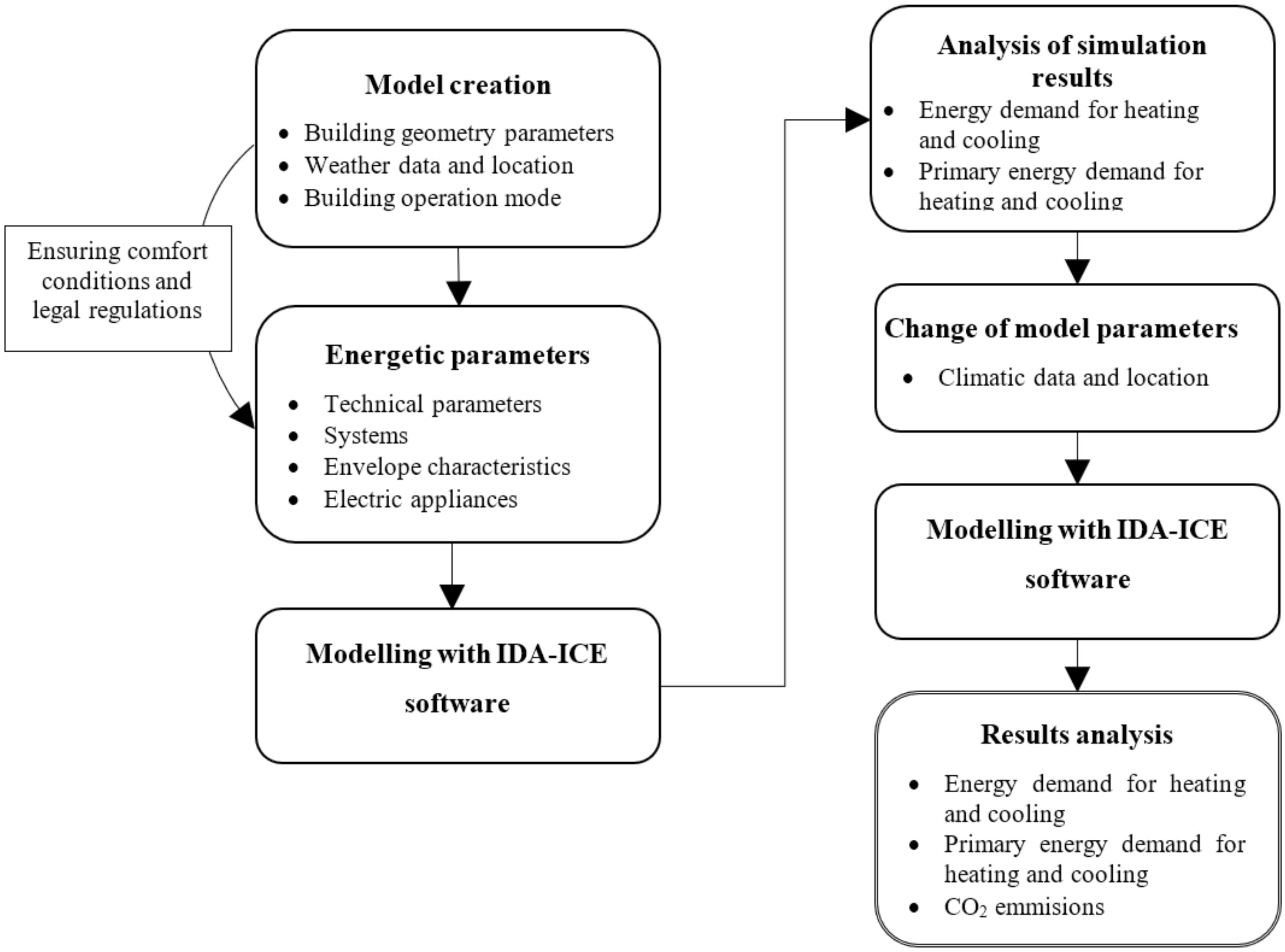

Figure 2. Study method (adapted by the authors in reliance on [29,30]).

The key data of the building's windows are presented in Table 5. The ratios were obtained from the IDA-ICE database. The type of window chosen is a quad-glazed window with in-between areas 90% filled with argon gas.

Table 5. Data of see-through building envelopes.

See-Through Envelopes	Solar Heat Inflow Ratio, g	Solar Permeability Ratio, T	Visible Permeability Ratio, T_{vis}	Interior Emission Ratio	Exterior Emission Ratio
Windows	0.60	0.55	0.74	0.837	0.837

The number and behavior of the residents have a large impact on the outcomes of energy calculations, which makes selecting the right data highly relevant. Table 6 contains the key usage mode parameters for the building model.

Notwithstanding the model of the state under analysis, these building usage parameters do not change in the course of modeling and remain the same for each building model. A visualization of the building in the environment of IDA-ICE 4.8 software used for dynamic simulation is shown in Figure 3.

Table 6. Building usage parameters.

Parameter	Comment
Energy consumption by electrical appliances	The annual consumption of electrical energy by household appliances in a residential district is 30 kWh/m^2 [31]
Lighting	630 kWh per residential home per year [31]
Energy for water heating	Hot water consumption per 24 h is assumed to be 75 L/person/24 h
Building occupancy	From 8 a.m. until 3 p.m. (or until 5 PM for one-half of the residents) on weekdays, weekends at home.
Resident activity level	0.77 MET. 1 MET = 58 W/m^2 of the body surface area (assumed to be 1.80 m^2) [31]

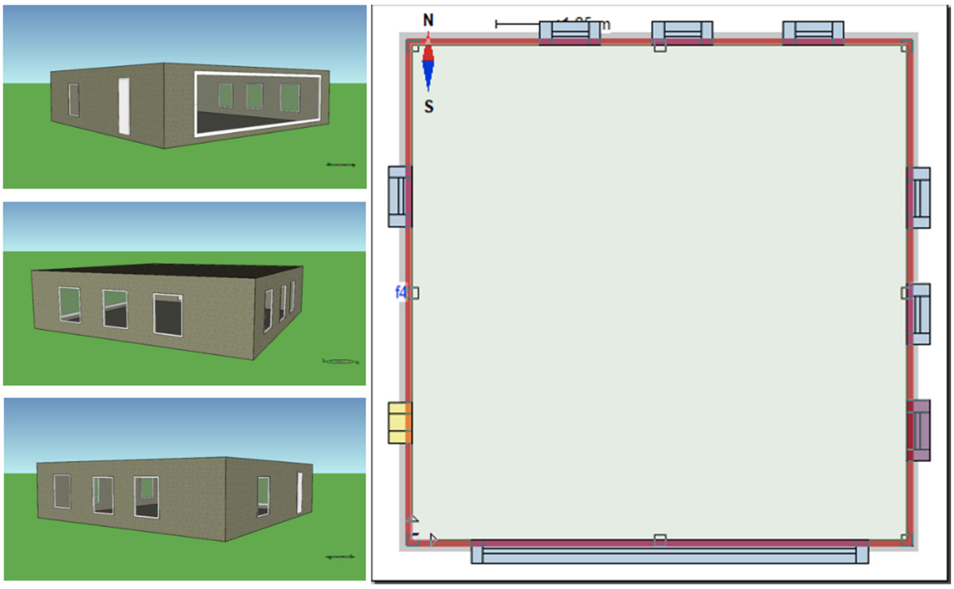

Figure 3. Visualization of the modeled residential home in the environment of IDA-ICE software.

2.2. Analysis of Energy Indicators of Buildings under Different Climatic Conditions

Each building model in IDA-ICE software is designed to conform to the principal requirements laid down in the building directives and standards of the subject country (Table 7) that apply to energy-efficient buildings, the main difference among the models being the envelope parameters and climatic data. Data such as building geometry, occupancy, number of residents, hot water consumption, and electrical energy consumption for electrical appliances remain the same across all building models covered by the analysis. A summary of the climatic data used in the models of the building analyzed is presented in Table 7, the key assumptions used for the purposes of the study are given in Table 8 and primary energy factors and CO_2 emission factors are presented in Table 9.

Table 7. Summary of study models.

Model No.	Climatic Data Used	Methodology Defining the Energy Characteristics of the Building, Which Is Used for Modelling Purposes
1	Vilnius, Lithuania	[25]
2	Jyväskylä, Finland	[32]
3	Palermo, Southern Italy	[33]
4	Bologna, Northern Italy	[33]
5	Copenhagen, Denmark	[34]
6	Lisbon, Southern Portugal	[35]
7	Bragança, Northern Portugal	[35]
8	Ljubljana, Slovenia	[36]
9	Warsaw, Poland	[37]
10	Oslo, Norway	[38]
11	Bregenz, Austria	[26]

Table 8. Study assumptions.

Indicator	Assumption
Scope of application	New buildings
Building type	A single-household residential home (100 m^2)
Climatic data	Vilnius, Jyväskylä, Palermo, Bologna, Copenhagen, Bragança, Lisbon, Ljubljana, Warsaw, Oslo, Bregenz
Established parameters	Envelopes (walls, floors, windows, roof, partitions), air flow, mechanical ventilation, heating, cooling, hot water, building usage mode, electrical energy consumption
Survey of energy indicators	Computer modelling using IDA-ICE software
Indicators analysed	Primary energy for heating and cooling, CO_2 emissions

Table 9. Primary energy factors (PEF) and CO_2 emission factors (EF) in subject countries.

Type of Energy	Country	PEF	kg CO_2/kWh	Comment
Central heating	Lithuania	0.62	0.100	Heat from heating systems, Lithuanian average
	Finland	0.50	0.195	EF average for Finland's central systems
	Italy	1.50	0.500	
	Denmark	0.60	0.260	
	Portugal	1.00	0.200	
	Slovenia	1.20	0.371	
	Poland	0.80	0.270	Central heating in Warsaw comes from a combined heat and power plant (fueled with coal)
	Norway	0.11	0.019	The CO_2 EF value was chosen with reference to the central heating technology in place in Oslo (based on wood pellet boilers and biofuel)
	Austria	0.19	0.200	
Central cooling	Finland	0.28	0.027	
	Italy	0.50	0.270	
Electricity	Lithuania	2.50	0.420	An average for different methods to generate electricity
	Finland	1.20	0.141	
	Italy	2.42	0.410	
	Denmark	1.80	0.420	
	Portugal	2.50	0.144	
	Slovenia	2.50	0.353	
	Poland	3.00	1.190	
	Norway	1.79	0.0022	
	Austria	1.91	0.176	
Natural gas	Lithuania	1.10	0.220	
	Finland	1.34	0.199	
	Italy	1.05	0.3696	
	Denmark	1.00	0.220	
	Portugal	1.00	0.202	
	Slovenia	1.20	0.200	
	Poland	1.20	0.201	
	Norway	1.244	0.203	
	Austria	0.19	0.200	

2.3. Climatic Data and Potential Climate Change Effect

Climate in Europe can be described as a mid-latitude climate with the following climate zones: Mediterranean, oceanic, continental, and Nordic [30]. Climate zones are defined on the basis of heating degree days (HDD) or cooling degree days (CDD). A heating/cooling degree day is a unit of measure for quantitative evaluation of the demand for heating/cooling in a building. A map of heating and cooling degree days in Europe is shown in Figure 4.

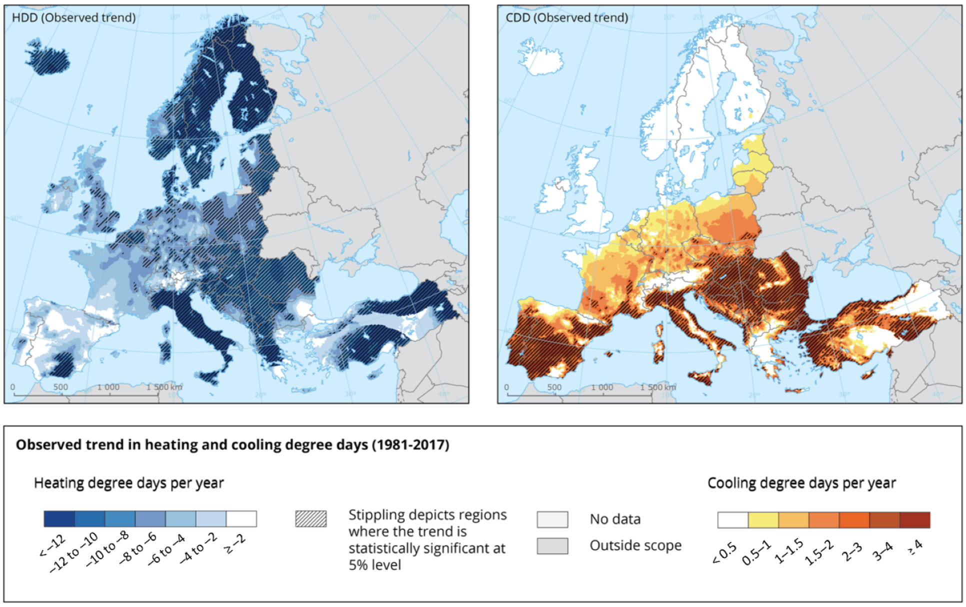

Figure 4. Heating and cooling degree days in Europe [39].

The climatic data used for the purposes of the modeling were obtained from the ASHRAE IWEC2 database using IDA-ICE software. ASHRAE stands for the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. This society has initiated a collection of typical climatic data across over 3000 locations worldwide, to be used in energy calculation and modeling programs. Every climatic data package contains hourly climatic data for the selected location: the outside air temperature, relative humidity, wind speed, solar irradiance.

3. Results of the Analysis of Primary Energy for Building Heating and Cooling

Following the analysis of the differences in heat transfer ratios applicable to efficient buildings covered in this chapter, the study proceeds with four separate cases and produces an appropriate set of results for each of them. A summary of these phases is shown in Table 10.

Table 10. Summary of phases of the analysis of the study.

Case No.	Analysis Details
Case 1	The energy indicators of an energy-efficient building in the European states covered by the analysis (thermal energy consumption for heating and cooling; primary energy for heating and cooling; primary energy consumption in the building when all of the subject countries use a typical source of energy)
Case 2	The energy indicators of an energy-efficient building in the European states covered by the analysis (thermal energy consumption for heating and cooling; primary energy for heating and cooling; primary energy consumption in the building when all of the subject countries use the same source of energy (natural gas for heating, electricity for cooling (the average of different ways to generate electricity); identification of CO_2 emissions)
Case 3	The energy indicators of a Lithuanian building, energy class A+, in the European states covered by the analysis (thermal energy consumption for heating and cooling; primary energy for heating and cooling; primary energy consumption in the building when all of the subject countries use the same source of energy (natural gas for heating, electricity for cooling (the average of different ways to generate electricity); identification of CO_2 emissions)
Case 4	The energy indicators of a residential building conforming to the regulations for new buildings in the European states covered by the analysis (Italy, Finland, Austria, Denmark, Portugal, Slovenia, Poland, Norway) under Lithuanian climatic conditions (thermal energy consumption for heating and cooling; primary energy for heating and cooling; identification of CO_2 emissions)

3.1. Comparison of Heat Transfer Ratios Applicable to Energy-Efficient Buildings

To be able to highlight the key differences in the regulations governing energy-efficient buildings in the states covered by the analysis better, a comparison of heat transfer coefficients (of walls and windows by choice) is carried out, its results are presented in Figure 5.

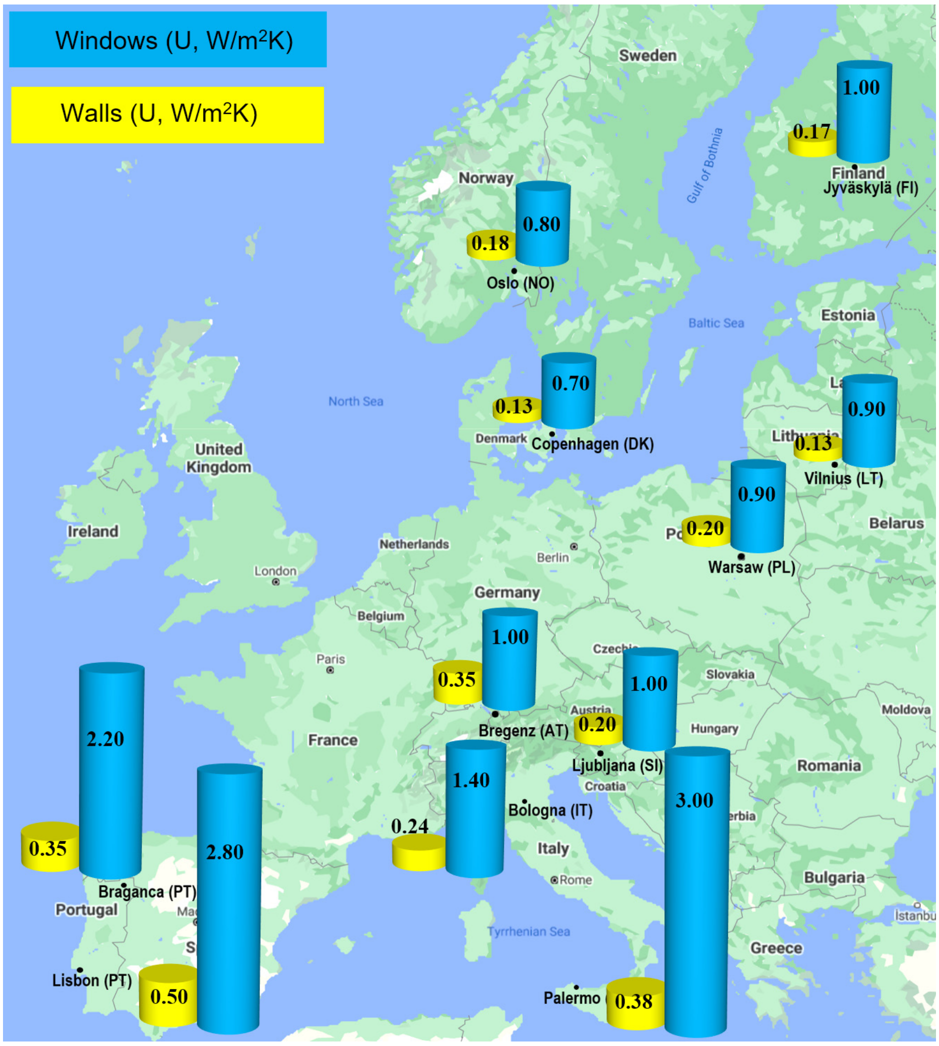

Figure 5. Heat transfer coefficient values of the exterior walls and windows of a building in the subject countries.

To achieve a set of standards on a par with an energy-efficient building with economically optimal measures, the focus must be placed first and foremost on different climatic conditions: insulation and airtightness of buildings are a must in colder climates, whereas high energy class equipment and efficient lighting are the number one measures to reduce the building's energy consumption in warmer European climate zones [30].

Figure 5 shows that the tightest requirements in relation to the values of building envelope heat transfer coefficients apply in countries with colder climates, such as Lithuania, Denmark, Finland, and Norway. In Denmark, the value of heat transfer coefficients in a class B2020 building is comparable with that which applies to a class A+ energy-efficient building in Lithuania. Higher heat transfer coefficient values for exterior walls and ceilings apply in southern and central Europe—Italy, Portugal, and Austria.

3.2. Case 1. Typical Source of Energy

The building model primary energy demands for heating and cooling in different European states using the typical sources of energy in those states and considering the different factors of primary energy conversion are presented first (Figure 6). The results of primary energy for heating and cooling of the calibrated model depending on the heat source LT A+ (similar to nZEB) building are 40–67 kWh/m^2/year (Figures 6 and 7), which shows that the model is suitable considering the requirements and recommendations (Figure 1).

The data presented in Figure 6 show that the highest level of consumption of primary energy for building heating and cooling purposes exists in Ljubljana, Slovenia, Warsaw, Poland, and Bragança, Portugal. Whereas the lowest aggregate primary energy demand for heating and cooling was obtained in buildings that conform to the national requirements for energy-efficient buildings that apply in Austria and Norway. It is important to mention here that the amount of primary energy used for building heating and cooling purposes in Denmark is similar to that in Lithuania (4.2 MWh and 4.0 MWh, appropriately). A building designed for the Lithuanian climate conforms to energy class A+, and for the Danish climate, to the B2020 label [34].

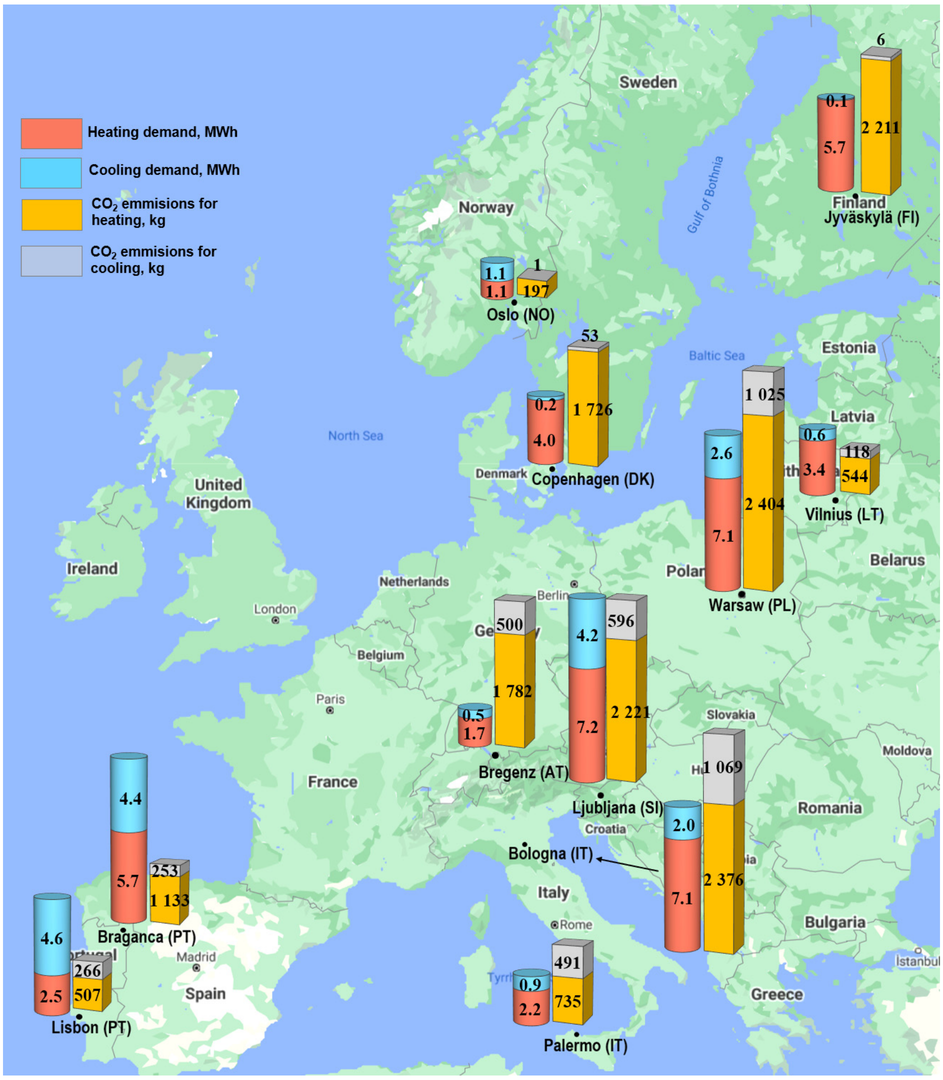

Figure 6. The aggregate primary energy demand for heating and cooling (MWh) in a building and the aggregate carbon dioxide emissions for heating and cooling (kg) with countries' typical sources of energy.

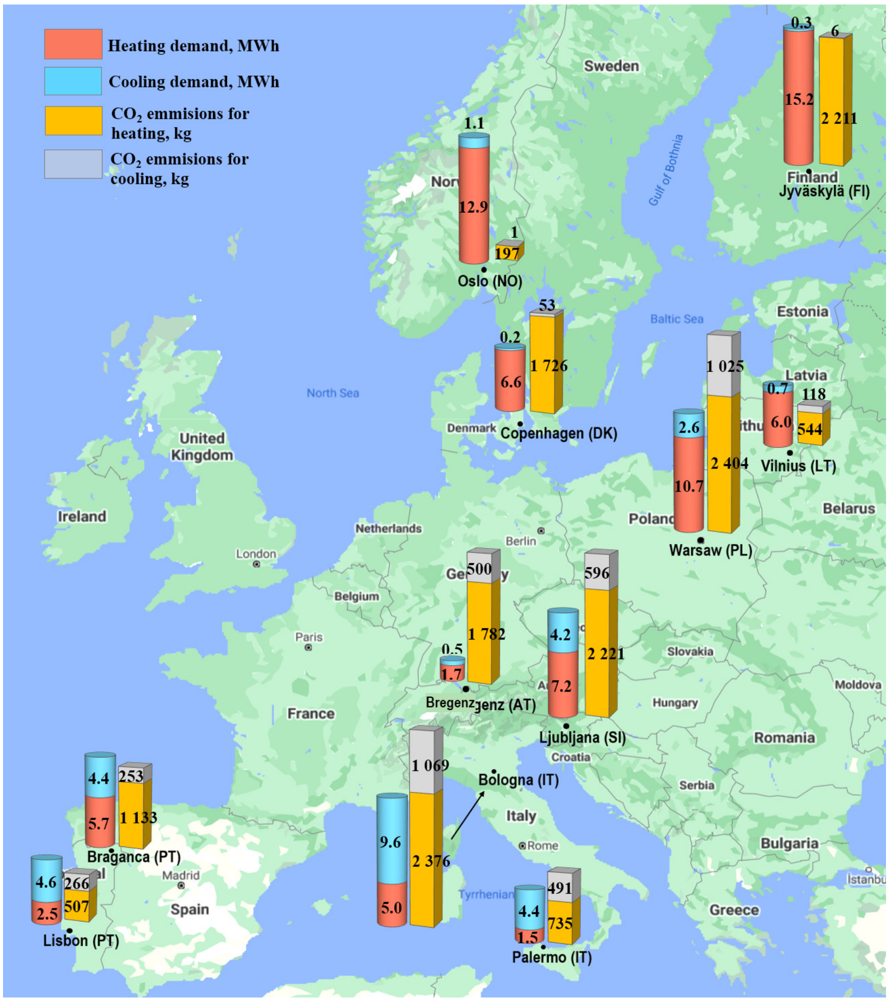

Figure 7. The aggregate primary energy demand for heating and cooling (MWh) in a building and the aggregate carbon dioxide emissions for heating and cooling (kg) using the same source of energy (natural gas for heating and electricity from RES and NER for cooling).

A building designed for the cold climate of Jyväskylä, Finland with its chilly winters and temperatures that drop to −27.9 °C (Tables 3 and 5) will consume 50% less primary energy compared to a building that exists in Ljubljana, Slovenia, and, for instance, 37% less primary energy compared to a building in Bologna, Italy. In Bologna, central heating is provided by a CHP plant (fueled with methane gas) [40], while the main fuel used in the central heating systems of Finland consists of peat and wood [41].

3.3. Case 2. The Same Source of Energy

The results shown in Figure 7 indicate the amount of primary energy (MWh) that would be required to satisfy the energy demands of a building if all models of the building use the same type of fuel (natural gas for heating and electricity from renewable energy sources (RES) and non-renewable energy resources (NER) for cooling).

The data shown in Figure 7 indicate that the highest demand for primary energy for heating and cooling with natural gas and electricity (from RES and NER) exists in a Finnish residential building. Compared to the original option (where the Finnish central systems use biofuel for heating and cooling purposes), the building's demand for primary energy goes up by 63%. In Lithuania, when the primary energy demands of a building are satisfied with natural gas, this gap stands at 40%. The largest difference can be observed in Norway: if Oslo used natural gas and electricity from NER instead of biofuel for heating and supply of electrical energy, the demand for primary energy would increase by 84%.

3.4. Case 3. Lithuania in Analysed European Countries

This analysis aims to determine the thermal consumption for heating and cooling in an energy class A+ building and the demands for primary energy in the European states covered by the analysis. To that end, the building model "Vilnius, Lithuania", its envelope heat transfer ratio values conforming to the values of energy class A+, is built on the bases of the climatic data of the subject states (for instance, the model "class A+ building in Palermo" shows results obtained by modeling an energy class A+ building with the climatic data for the city of Palermo, stating in the model that the building is located in the city of Palermo).

Figure 8 shows the aggregate demand for primary energy to secure the heating and cooling needs of an energy class A+ building in the subject countries. The same figure also shows the aggregate carbon dioxide emissions. The primary energy and the CO_2 emissions are calculated with PEF and EF values applied in the countries covered by the analysis (for instance, with the model "class A+ building in Palermo", primary energy and CO_2 emissions are calculated using PEF and EF as applicable in Italy).

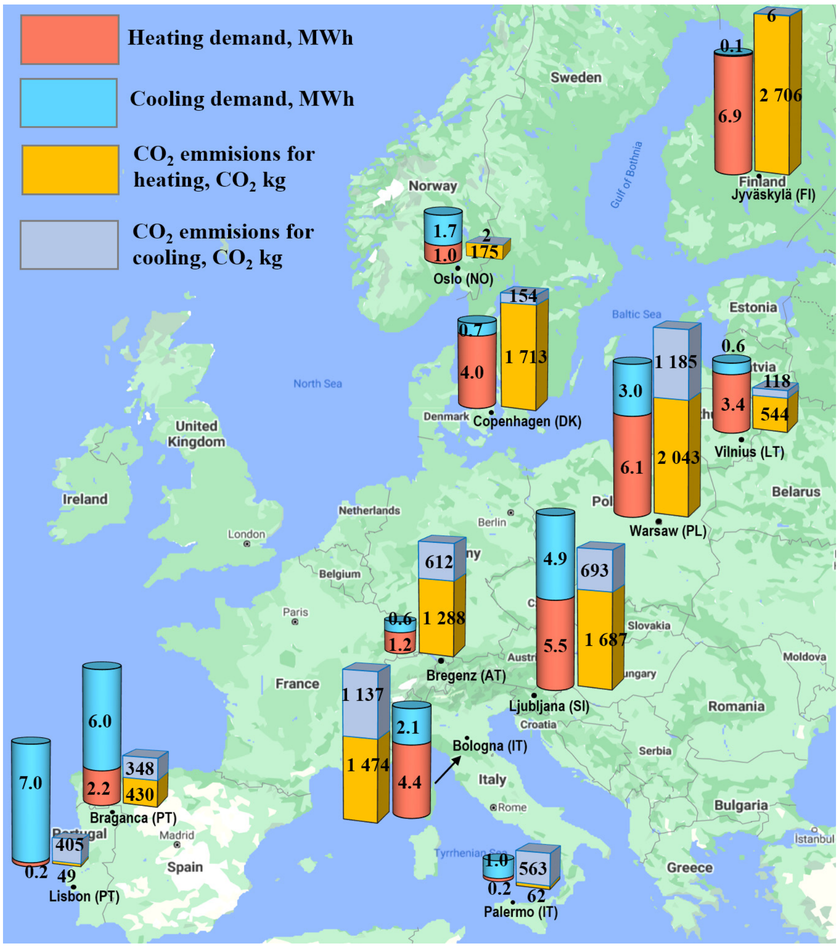

Figure 8. The aggregate primary energy demand for heating and cooling (MWh) in an energy class A+ building and the aggregate carbon dioxide emissions for heating and cooling (kg) in different European climate zones.

The data in Figure 8 show that the highest demand for primary energy in an energy class A+ building would exist if the building were located in typical central European climate in Ljubljana, Slovenia, where said demand would be about 61% more than if the building were located in Lithuania. The largest CO_2 emissions would occur if the building model in question were located in Warsaw, Poland, surpassing the CO_2 emissions in Lithuania by 79%, the smallest, in Lisbon, Portugal, falling 39% below the Lithuanian level.

3.5. Case 4. Analyzed European Countries' Buildings in Lithuania Climate

In this case, the modeling results covered by the analysis were obtained by modeling buildings in the subject countries with the climatic data for the city of Vilnius. The aim here is to identify the demands for primary energy if the building models of the subject countries were located in Vilnius and exposed to the Lithuanian climate.

Figure 9 shows the total demand for primary energy for heating and cooling in buildings of the European states covered by the analysis, as well as the total amount of carbon dioxide emissions under prevalent Lithuanian climatic conditions. The primary energy and the CO_2 emissions were calculated with the PEF and EF values that apply in Lithuania (heating from heating systems, the Lithuanian average, and the average of different methods to generate electricity; see Table 9 for details).

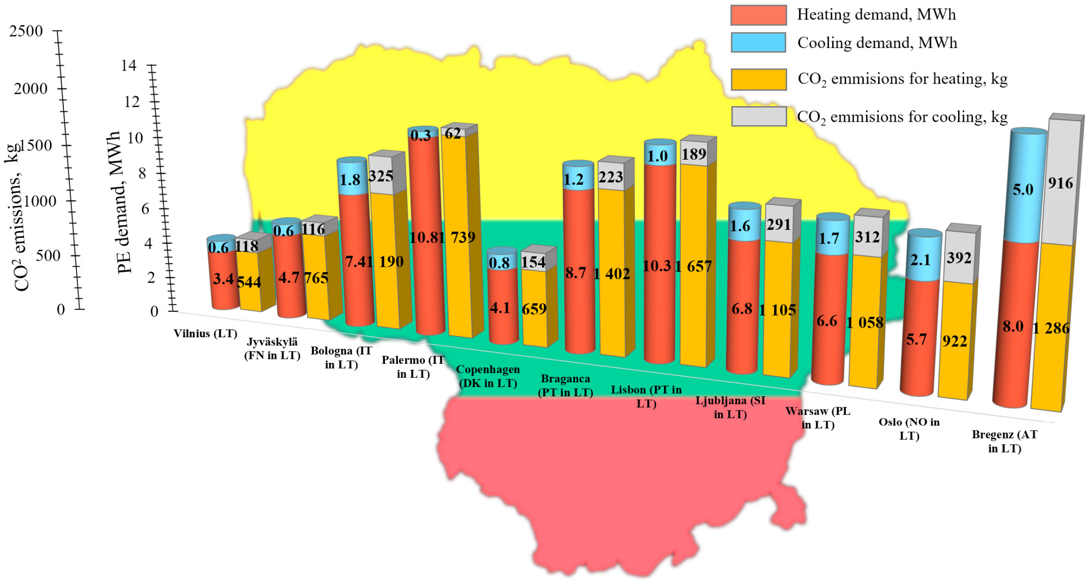

Figure 9. The aggregate primary energy demand for heating and cooling (MWh) in a building and the aggregate carbon dioxide emissions for heating and cooling (kg) in Lithuanian climatic conditions.

So, the data in Figure 9 indicate that under prevalent Lithuanian climatic conditions, the highest level of consumption of primary energy would exist in a building that matches the Austrian residential house model. With the Lithuanian climatic conditions prevalent, this building would consume 70% primary energy more compared to the Austrian consumption level (yet its CO_2 emissions would drop by 7%).

3.6. Discussion

From 2016 to 2022, Lithuania underwent significant changes in the regulation of energy efficiency in buildings. This has led to a reduction in the U-values of buildings and an increase in the use of renewable energy to meet energy needs. The study aimed to analyze what these changes look like at the European level. It is obvious that the tightest requirements for the heat transfer of building envelopes (exterior walls and windows) exist in northern Europe (such as Denmark and Lithuania), and the highest permissible heat transfer coefficients are in southern countries (such as Portugal and Italy).

Furthermore, it should be emphasized that, in determining the primary energy of electricity (which is very important when using heat pumps), the fuels used for production are often difficult to define due to common electricity networks. Therefore, it is most appropriate to compare the heating and cooling demands "up to" the heat source. This study did not address energy efficiency alternatives and the inclusion of additional RES to increase the sustainability of the building, so in the future it is planned to examine the energy performance of energy buildings in a broader perspective, taking into account not only climatic differences but also applied technological alternatives and architectural solutions.

Finally, going back to the beginning, not all buildings in the countries surveyed meet the required, recommended primary energy consumption values for heating and cooling. The purpose of this study was to compare and illustrate these differences and to highlight that good practice can be shared.

4. Conclusions

Four analyses with different viewpoints were performed in the study. This included such cases as the single-family building in subject countries used a typical source of energy; the same source of energy; Lithuanian building of A+ energy class is placed in other countries, and the simulated buildings are in Lithuanian climate. The outcomes of the simulations were as follows:

- The results of the different analyses performed within the scope of this study have shown the gap in the demand for primary energy in a building located in Denmark and one located in Lithuania to be the smallest, standing at about 9%. The biggest difference can be seen between the energy indicators of a high energy class building in Palermo and those of an energy class A+ building: if a Palermo residential building was operated in Lithuania, its primary energy demand for heating and cooling would surge by 88% compared to a building located in Palermo. The annual volume of thermal energy consumed for heating is the highest in the building model that mirrors the Finnish energy-efficient building. An energy class A+ building based in Lithuania requires 52% less thermal energy to satisfy its heating demands per year compared to Finland. The lowest value of thermal energy consumption for cooling is observed in a class B2020 building located in Copenhagen, Denmark. Compared to Lithuania, this building will use 55% less thermal energy for its cooling needs than an energy class A+ building in Lithuania.
- The largest amount of primary energy and CO_2 emissions to satisfy the heating and cooling demands of a building is consumed in Ljubljana, Slovenia (11 MWh), Warsaw, Poland (10 MWh), and Bragança, Portugal (9 MWh), whereas the lowest demand for primary energy and CO_2 emissions for heating and cooling was observed in buildings that conform to the Austrian and Norwegian national requirements for energy-efficient buildings, standing at about 2.0 MWh of primary energy.
- The highest demand for primary energy and CO_2 emissions for heating and cooling with natural gas and electricity (from RES and NER) exists in a residential building in Finland. Compared to the original option (where the Finnish central systems use biofuel for heating and cooling), the building's demand for primary energy rises by 63%. In Lithuania, if the demand for primary energy in a building is met with natural gas, this difference stands at 40%. The lowest degree of primary energy consumption with natural gas and electricity (from RES and NER) would exist in an Austria-based building: 2.2 MWh.
- Under prevalent Lithuanian climatic conditions, the highest level of primary energy consumption and CO_2 emissions would exist in a building that corresponds to the Austrian residential house model. Under such conditions, the building would consume nearly 70% more primary energy than under ordinary conditions, as they exist in Austria. In Lithuania, the smallest amount of primary energy under prevalent Lithuanian climatic conditions would be consumed by a Lithuanian energy class A+ building: 4 MWh of primary energy.

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Nomenclature

U	overall heat transfer coefficient, W/(m^{2}K)
Abbreviations	
BPIE	Building Performance Institute Europe
CDD	Cooling Degree Days
EC	European Commission
EF	Emission Factor
EU	European Union
GHG	Greenhouse Gas
HDD	Heating Degree Days
NER	Non-renewable Energy Resources
NZEB	Nearly Zero-Energy Building
PE	Primary Energy
PEF	Primary Energy Factor
RES	Renewable Energy Sources
RPC	Representative Concentration Pathway

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