



Original Research Article

Impact of Future Changing Climate on the Energy Demand of Finland's Building Stock

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ABSTRACT

This study examines the energy demand of the building stock in Kanta-Häme, Finland, through simulations with the dynamic, multi-zone simulation software IDA Indoor Climate and Energy. Four buildings with varying materials, construction years, and purposes were examined. Heating and cooling energy requirements were evaluated using the current climate Test Reference Year 2020, with future projections based on Representative Concentration Pathways 4.5 and 8.5 for Test Reference Years 2030 and 2050. The findings suggest that, compared to the 2020 baseline, cooling demand increases while heating demand decreases under both scenarios. For all buildings, the heating energy demand was found to decrease by 2050, from 9.9% to 24%, depending on building type and climate scenario. For the two buildings with installed cooling systems, the cooling energy demand increased from 8.4% to 44.3%, while the total energy demand decreased from 9.4% to 18.1% across climate scenarios and cooling techniques. This result indicates an overall decline in future total energy demand. The other two buildings without installed cooling systems showed signs of severe overheating, one of them even in the Test Reference Year 2020, and up to 97% in Representative Concentration Pathway 8.5 Test Reference Year 2050. Hotter summers will increase the need for cooling to prevent overheating, mitigate discomfort and associated health risks, particularly among vulnerable populations. The main challenge concerns existing buildings, particularly those without cooling systems.

KEYWORDS

Building energy simulation, Energy demand, Indoor climate, Subarctic climate, Built environment.

INTRODUCTION

The effects of global warming are resulting in hotter weather and more heat waves [1]. Climate scientists have repeatedly warned governments of devastating future consequences of extreme weather if we do not seriously commit to mitigation and adaptation actions [2]. In response, the European Union (EU) has committed to combat climate change [3]. In line with this, unique circumstances are identified in subarctic regions such as Finland, where average summer temperatures are projected to increase by 2.4 °C during the period 2040–2069 [4]. Furthermore, in 2024, Finland's temperature was 3.4 °C higher than in the pre-industrial era [5]. This rise in temperature creates challenges for buildings regarding overheating. Pulkkinen *et al.* [6] examined how climate change affects building thermal energy demand in Finland using

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building sector is facing environmental, technical, economic, and social challenges due to a warming climate. The increasing summer overheating requires solutions to mitigate discomfort among building occupants.

In the EU, the building sector is responsible for approximately 40% of the energy consumption and around 36% of the greenhouse gas (GHG) emissions [7]. This situation is a key focus area in the drive to decrease energy use and GHG emissions. The building sector is projected to significantly contribute to the accelerated achievement of the EU's GHG target of 55% reduction by 2030 compared to 1990 levels and climate neutrality by 2050 [3]. At the national level, various policy and regulatory instruments aim to reduce energy demand in buildings [8]. Since 2020, each member state has been responsible for supporting the construction of Nearly Zero Energy Buildings (nZEBs). National building codes vary according to each country's priorities and energy mix, which influence the building indicators and criteria specified within these regulations [9]. The country-specific building codes aim to cover energy performance compliance or rating. Allard *et al.* [10] emphasise that building codes constitute an effective policy tool for lowering energy use in buildings. Considering that 85% of buildings in the EU were constructed before 2000, and that 75% exhibit poor energy performance [3], this indicates that greater emphasis should be placed on renovation efforts to reduce emissions. Ruosteenoja & Jylhä [4] articulate the importance of preparing and adapting the building sector to a 2.0 °C increase in global temperatures.

There is evidence that mortality rates increase during heatwaves. This has been confirmed by the World Health Organisation (WHO) [11] and, from the Nordic perspective, by Kollanus *et al.* [12]. Mitigating the impact of prolonged heatwaves on building occupants is a critical concern and should be considered. This can be accomplished by designing indoor climates in accordance with established regulations to prevent and reduce overheating. However, buildings constructed according to outdated standards may no longer provide a healthy indoor environment in the future [13]. Decrees issued by the "Finnish Ministry of Social Affairs and Health" (545/2015) and "Ministry of Environment" (1009/2017) set limits for building heating and cooling [14], [15].

As global temperatures increase, demand for cooling energy will rise, as already visible in near-future scenarios. Increased cooling demands in buildings worldwide are attributed to global warming, changes in demographics (population growth, urbanisation, and an ageing population vulnerable to elevated heat levels) and economic growth (increased living standards) [16]. Increased use of active cooling systems significantly impacts overall energy demand in terms of energy provision and the resulting emissions. A report by the International Energy Agency (IEA) highlights that energy demand for space cooling accounts for approximately 20% the total energy consumed by buildings worldwide [17]. Combining passive strategies with low-emission active cooling methods is recommended by the EU [16]. Solutions that utilise contemporary design approaches encouraging passive cooling strategies, such as effective insulation, natural ventilation, shading and thermal mass, can significantly reduce reliance on active cooling systems that depend on external energy sources, such as electricity. Passive cooling methods are increasingly used to combat rising temperatures from climate change, reduce high energy demand, and lower GHG emissions. For example, Bugenings and Kamari [18] studied 25 real-world building projects in Denmark that utilised bioclimatic architectural design. The analysis indicated that passive heating and passive cooling measures will remain relevant in research and in practise, with passive cooling methods likely to gain increasing importance given rising outdoor temperatures. Hannoudi *et al.* [19] explored the effects of passive heating and cooling through the concept of a multi-angled window using IDA ICE simulations. The simulations showed improved visual comfort, increased daylight availability, and reduced spatial energy demand. Turhan *et al.* [20] found that green roofs and walls can reduce energy demand and improve thermal comfort.

Building energy modelling and simulation enable evaluation of energy use and occupant comfort while identifying opportunities to reduce energy demand and GHG emissions [21].

Research into the optimisation of heating, ventilation, and air conditioning (HVAC) systems to improve efficiency and minimise GHG emissions is increasingly carried out. For example, Akyol *et al.* [22] used physics-based Urban Building Energy Models (UBEM) to model building performance in future scenarios in Turkey. Schroderus *et al.* [23] integrated occupant surveys, physical measurements, and IDA-ICE simulations to assess the comprehensive effects of energy retrofits on indoor environmental quality, energy consumption, and the future climate resilience of a building located in the Tampere region of Finland. Simulation models for case building were developed both before and after the implementation of the energy retrofit. Wilk-Slomka *et al.* [24] used Environmental Systems Performance – Research (ESP-r) software to simulate a low-energy building in Poland. They found that the building will require additional active cooling under future weather scenarios. Chi *et al.* [25] used Agent-Based Modelling (ABM) to analyse the impacts of climate, occupant behaviour and urban morphology on building energy demand in a cold region of China. They simulated the energy demand of 4754 buildings in Harbin, China, under complex behavioural conditions.

Nevertheless, there is limited research on the impacts of climate change on the energy demand of Finland's building stock. Some studies have been conducted in other regions in Finland, such as Tampere [23] and Helsinki [13]. Here, the Kanta-Häme region was chosen due to funding for research on the effects of future weather conditions on the building stock in the area, as no such research has been carried out so far, according to the literature review. This study is novel and distinguishes itself by analysing the energy performance of buildings in the Kanta-Häme region, in the context of future climate projections. The aim is to deepen understanding of the effects of climate change on the building stock in the region and, subsequently, in Finland and similar subarctic regions. In addition, the aim is to support regional stakeholders in understanding the future challenges and preparing their mitigation and adaptation actions.

The main research question of this study is “How does the changing future climate affect buildings' energy demand in the Kanta-Häme region and subsequently in Finland and similar subarctic regions?”

The hypotheses of this study are:

H1: The building stock in Finland will face increased cooling energy demand in the future.

H2: The overall annual energy demand of buildings in Finland will decline in the future.

METHOD

Climate modelling and climate change scenarios are increasingly used to improve understanding and awareness of the causes and effects of climate change, and to inform proactive mitigation measures. The “Intergovernmental Panel on Climate Change” (IPCC) serves as a driving force in developing various future emission projection scenarios. Future scenarios are used to investigate the impacts of future climate change on ecosystems and potential responses to climate change [26]. Scenarios also allow comparisons across diverse research outcomes.

Representative Concentration Pathways

Scenarios based on RCPs are labelled as RCPy, where “y” denotes radiative forcing (RF) levels of 2.6, 4.5, 6.0, and 8.5 W/m². These scenarios were developed under different assumptions for the period 1850–2100 regarding energy use and emissions, including increases in CO₂ concentrations and temperature, and changes in precipitation patterns [27]. In this study, RCP4.5 and RCP8.5, commonly used in building energy analyses, are applied as future climate projection datasets for the building simulations.

RCP4.5 represents a stabilisation scenario in which radiative forcing reaches 4.5 W/m² shortly after 2100 without exceeding this level. It assumes that countries implement effective

emission mitigation measures across all sectors of the economy, including agriculture and land use [28].

RCP8.5, in contrast, reflects a high-emission pathway with no significant emission reduction efforts. Under this scenario, CO₂ emissions continue to rise, reaching levels approximately three times higher in 2100 than today. The absence of specific climate policies results in high energy demand and substantial GHG emissions [29].

RCP4.5 and RCP8.5 are commonly used in building energy simulations because they represent moderate and high GHG emissions, offering a wide view of possible future climates. RCP2.6 represents an aggressive mitigation pathway that is less likely to occur given current trends. We did neither include the RCP6.0 as it is a rarely used scenario, nor the RCP-SSP (Shared Socioeconomic Pathways) scenarios, because they are not included in the “Finnish Meteorological Institute” (FMI) [30] scenarios that we use for our study.

Indoor climate design values

In Finland, the “Ministry of Social Affairs and Health has issued a decree on the health conditions of dwellings and other living spaces” (545/2015), establishing specific temperature limits. According to this regulation, indoor temperatures in residential dwellings must be maintained between 18 °C and 26 °C during the heating season and between 18 °C and 32 °C outside the heating season [14]. In service buildings, such as retirement homes, childcare facilities, and educational institutions, the required indoor temperature range is 20 °C to 26 °C during the heating season and 20 °C to 32 °C outside the heating season.

In addition to the health decree, Decree 1009/2017 of the “Ministry of the Environment” of Finland establishes heating limits during the planning and construction of new buildings [15]. The limits are 20–25 °C within the heating season and 20–27 °C outside the heating season. These limits are used when modelling and simulating buildings. Finland uses both decrees, but they are applied in different phases of the building’s life. 1009/2017 is used first in planning and applies to all new buildings, and 545/2015 applies to all dwellings and other living quarters.

Additional factors, including ventilation in living spaces and indoor CO₂ concentration, should be considered when designing healthy residential environments. According to Decree 545/2015, a minimum ventilation rate of 0.35 dm³/s per square metre is required in all dwellings during the occupied periods [14]. Furthermore, the decree establishes a threshold of 2100 mg/m³ (or 1150 ppm), which is higher than the outdoor CO₂ concentration, beyond which mitigation measures should be implemented.

SIMULATION ENVIRONMENT

Simulations of future climates were carried out using the IDA Indoor Climate and Energy (ICE) software. This software was developed by the Swedish company EQUA in 1998. Since then, it has been updated, and the version used to carry out the simulations in this study is 5.1. IDA ICE is a dynamic simulation software used to study indoor climate and a building’s energy demand. The IDA ICE simulation tool has been used in previous research on building simulation, such as [13], [31].

IDA ICE simulates buildings using multi-zone, time-dependent models. Each zone is calculated with high temporal resolution, often with adaptive time steps, enabling precise modelling of temperature and energy flows. It has solvers capable of iterative solution of nonlinear equations, adaptive time stepping for improved accuracy during rapidly changing conditions, and component-based equation solving. The tool computes the design heating load, cooling loads (peak and time-based), zone-level and system-level energy flows. It is a full-year energy simulation tool that includes space heating and cooling demand, domestic hot water (DHW) demand, fan/pump electricity use, lighting and internal gain, system losses, and primary energy (and CO₂ emissions, which were not examined in the study). In the simulation tool, the buildings are modelled after real-life geometry and material data imported via industry

foundation classes (IFC) and two- and three-dimensional (2D/3D) computer-aided design (CAD) models from building owners or architects.

Based on current and future weather scenarios, shown in **Figure 1**, the projected changes in heating and cooling energy demand were examined. Four buildings were studied, including three with actual energy demand data, which was crucial for verifying the IDA ICE results. The buildings selected for simulation are residential and educational, with different building materials and construction years. Future weather scenarios were analysed to assess how energy consumption and indoor climate conditions may evolve. All study cases were first simulated under the current weather scenario TRY2020 and then compared with simulations done with the future scenarios. The results showed that surrounding structures, building height, orientation, window size and type affected potential overheating and the consequential cooling demand.

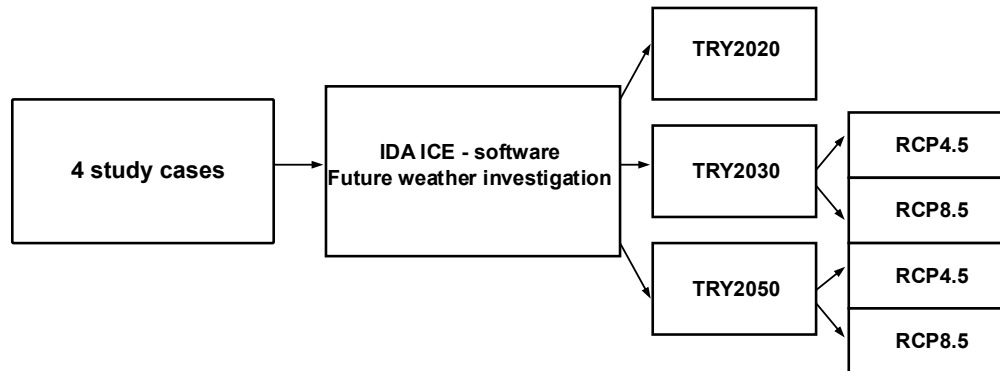


Figure 1. Scenarios generated for building simulation with weather data from FMI

Study Cases

The four study cases are located in the Kanta-Häme region in southern Finland, as shown in **Figure 2**. In all case studies, vegetation in the vicinity of the buildings was not included in the models to make the simulation process smoother and faster, and the windows were assumed to be always closed. **Table 1** shows the different building construction elements: materials, stratigraphy, and thermal insulation.



Figure 2. Kanta-Häme region

Residential Buildings

The study included two residential blocks of flats built in the 1950s and in the 1990s, respectively. They are both connected to the district heating (DH), which is used to warm spaces via water-circulating radiators (R) and heat DHW. Both buildings have mechanical extraction ventilation (MEV). The older building (building 1) was extensively renovated in

2004–2006, with modifications affecting the envelope structures. This information served as the basis for the U-value selections made when creating a model in the IDA ICE software.

Building 2, the newer one, is still in its original condition, with only a few bathrooms renovated. However, due to the lack of more precise information on the renovations, the bathroom changes were neglected. The two residential buildings are geometrically very different: the older one is 9 floors tall with a relatively small footprint, whereas the newer one is 3 floors tall and has a significantly larger footprint. The first one has a tower-like shape, whereas the second one has an L-shape. **Figure 3** shows the 3D models of the two buildings created in IDA ICE, including their orientations.

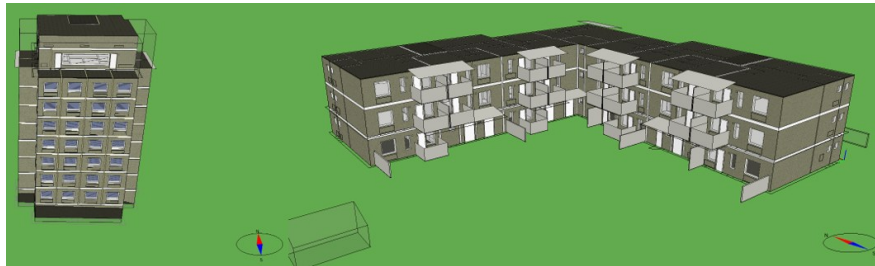


Figure 3. 3D models of building 1(left) and building 2 (right) in IDA ICE software

The buildings were modelled to resemble the existing buildings; however, in both cases, the roofs were simplified to flat roofs. The windows were assumed to be always closed, since opening them during the hottest time of the day would only further worsen overheating [32]. Nonetheless, they can help cool down the indoor space when opened, especially when the outside temperatures drop, such as at night. Building occupation times were estimated according to the Finnish building code 1010/2017, attachment 1, based on building class [33].

Both buildings come with window blinds installed in the gap between the inner and the outer glass. Window blinds are an effective way to prevent sunlight from entering the building, helping mitigate overheating in the cooling season.

The two residential buildings were first simulated under the current weather scenario TRY2020 for comparison and to ensure they were modelled correctly, and that the energy demands matched the real ones. TRY2020 has been validated by FMI in [34]. Afterwards, the two study cases were simulated in TRY2030 and TRY2050, with RCP4.5 and RCP8.5. The overheating limit was set to 27 °C, with a maximum of 150-degree hours in each zone. Degree hours are calculated by multiplying the number of degrees above the 27 °C limit for residential buildings by the duration in hours. For example, 30 °C for 2 hours equals 6 degree hours [33].

Building 1 is already overheating under current weather conditions due to the lack of shading elements (e.g., balconies) and the building's geometry; the south-facing facade is mostly covered by windows. The building is connected to the DH line, and the heat is distributed to the spaces via water circulating radiators (R). Actual consumption for building 1 was 270 MWh, while the TRY2020 simulation yielded 285 MWh (+6% relative to actual data).

Building 2 is less prone to overheating due to its geometry and the several shading elements on the south- and west-facing facades. In the current weather scenario, overheating is not observed; however, in future weather conditions, it will be necessary to investigate cooling options. Similar to building 1, the heating system is DH with radiators as the distribution method. Actual consumption data for building 2 varied across years due to varying winter severity, affecting heating-season energy demand, from 223 to 280 MWh (up to 25.5% variation in real-life consumption data). Simulated consumption in TRY2020 was about 284 MWh (+1.3% from actual data). **Table 1** shows the construction materials of each building.

Table 1. Building construction elements: materials, stratigraphy, and thermal insulation

Structure	Building 1	Building 2	Building 3	Building 4
Floor slab	Towards heated space: Linoleum sheet (plastic floor covering) 5 mm. Lightweight concrete 20 mm. Air gap 50 mm. Lightweight concrete 170 mm. Slab towards ground (before basement, warm space): Linoleum sheet 50 mm. Lightweight concrete 20 mm. Concrete 200 mm. Expanded polystyrene board 207 mm. Towards unheated space: Lightweight concrete 20 mm. Concrete 100 mm. Wood-wool board 150 mm. Concrete 150 mm. Sand 200 mm. Natural subsoil 150 mm.	Render mortar 5 mm. Concrete 265 mm. Expanded polystyrene board 130 mm. Ventilated air cavity 50 mm. Sand 50 mm. Acrylic sheet 20 mm. Soil 200 mm.	Towards unheated space: Linoleum sheet flooring 2 mm. Lightweight concrete 80 mm. Mineral wool board (heavy) 200 mm. Expanded clay aggregate (LECA) 300 mm. Towards heated space: Lightweight linoleum flooring 5 mm. Lightweight concrete 20 mm. Concrete 200 mm. Expanded polystyrene board 207 mm.	Towards heated space: 1) Linoleum sheet 15 mm. Lightweight concrete 80 mm. Hollow-core concrete slab 320 mm. 2) Linoleum sheet 10 mm. Lightweight concrete 80 mm. Hollow-core Slab 320 mm. Towards unheated space: Linoleum sheet 15 mm. Lightweight concrete 80 mm. Hollow-core concrete slab 320 mm. Polyurethane insulation plates 170 mm. Ventilated air cavity 1500 mm. Coarse gravel 200 mm. Plastic film 0.2 mm.
	External walls	Render mortar 10 mm. Concrete 150 mm. Mineral wool 150 mm. Ventilated air gap 70 mm. Lightweight concrete blocks 100 mm. Render mortar 10 mm.	Concrete 80 mm. Mineral wool 150 mm. Lightweight concrete blocks 80 mm. Render mortar 5 mm.	Gypsum board 13 mm. Wood-fibre board 48 mm. Polyamide film 1 mm. Framed structure cc600 with insulation 198 mm. Wood-fibre board (wind barrier) 90 mm. Air gap 48 mm. Wood 23 mm.
Roof / Upper slab	Render mortar 10 mm. Concrete 90 mm. Mineral wool 180 mm.	Drywall 13 mm. Concrete 200 mm. Mineral wool 200 mm.	Bitumen membrane 10 mm. Mineral wool board (heavy) 486 mm. Concrete 150 mm. Render mortar 10 mm.	Bitumen membrane 10 mm. CLT board 25 mm. Ventilated air gap 150 mm. Windproof rock wool insulation 50 mm. Rock wool insulation 400 mm. CLT board 25 mm.

Educational Buildings

Two educational buildings were chosen as cases for this study: building 3, built in 2020, and building 4, built in 2024.

Building 3 is a city-owned kindergarten built in 2020. It serves around 50 children and 20 members of staff. The building has rooms for three groups of children, a shared space for eating and other activities, and a kitchen and an office for the staff. The building has a floor area of 887 m² and a timber structure for exterior walls and roof, with the floor on the ground. The building's heating demand is handled through a concrete slab and a ground-source heat pump (GSHP), and it is distributed to the zones by water-circulating underfloor heating (UFH). As a modelling assumption, the GSHP unit modelled can provide enough heat for the building. Mechanical ventilation with heat recovery (MVHR) covers the ventilation needs. It has a central cooling coil that provides cooling via the central air handling unit. The kindergarten has 18 photovoltaic solar panels on the south-facing roof that, according to simulation, produce 2138 kWh each year. **Figure 4** shows the 3D model of the building in IDA ICE software. Actual consumption from building 3 was 107 MWh, and the simulated value was about 107.9 MWh (+0.8% relative to actual data).



Figure 4. 3D model of building 3 in IDA ICE software

Building 4 is a modern research and educational facility equipped with advanced systems and technical solutions. It accommodates research spaces, laboratories, and teaching facilities, and hosts a degree programme in food engineering and biotechnology as well as activities within the Smart-Bio key ecosystem. The building is 13 m high and comprises of two floors and an attic, with a total net floor area of 2,156 m². Precast reinforced concrete serves as the primary structural material. **Figure 5** shows the 3D view of building 4 created in IDA ICE, including its orientation. This building has no actual consumption data because it is a new building; the simulated consumption in TRY2020 was 209.0 MWh



Figure 5. 3D view of building 4 in IDA ICE software

The building's heating and cooling demands are managed by its building plant. The system features a GSHP with a capacity of 10 kW and a coefficient of performance (COP) of 4,

supported by six 330 m deep boreholes and a DH top-up source. Two thermal storage tanks, each with a capacity of 1 m³, store hot and cold water separately. For cooling, a 10 kW compression chiller is connected to an ambient air heat exchanger that supplies the air handling unit (AHU) cooling coils. In addition, the GSHP directly provides cooling to space-specific fan coil units. Space heating is mainly with waterborne UFH, except for five spaces heated with waterborne radiators. The ventilation system consists of four AHUs. Three of them have cross-flow plate heat exchangers (HX) with night-flush ventilation control, and one has an enthalpy wheel HX. All the AHU fans have variable air volume control.

Basic information regarding the four study cases, such as construction year, heating and ventilation types, heating system, floor area and volume, is summarised in **Table 2**. The table also includes the occupancy ratio (hours of the day divided by days of the week). This ratio is used in the simulation tool to determine the impact of building use, including heat load from people and the operation times of equipment, such as mechanical ventilation.

Table 2. Basic information of the four study cases used as input values in IDA ICE

Study case	Constr. year	Heating type	Ventilation type	Heating system	Floor area [m ²]	Volume [m ³]	Cooling system	Number of occupants	Occupancy ratio h/days]
Building 1	1950s	DH	MEV	R	1727	4412	No	54	24/7
Building 2	1993	DH	MEV	R	1682	4200	No	58	24/7
Building 3	2020	GSHP	MVHR	UFH	887	2442	Yes	178	8/5
Building 4	2024	GSHP+DH	MVHR	UFH+R	2156	7348	Yes	428	8/5

The four buildings were built in different years and have different heating systems. General information on the buildings' U-values and air leakage (q₅₀) is collected in **Table 3**. Infiltration rates are calculated as in the Finnish building code 1048/2017 [35]. Building orientation and U-values affect the heating demand. Minimising U-values reduces heat transfer rates between building components and, in turn, heat demand. Building orientation (moving large windows from the south and west facades to the north) theoretically decreases the cooling energy demand [36]. Modelling was limited to real-life buildings; therefore, changes to these components are out of scope of this study.

Table 3. U-values and infiltration value of the building envelopes as input values in IDA ICE

	Building 1	Building 2	Building 3	Building 4
Base floor [W/(m ² ·K)]	0.22	0.40	0.12	0.16
Outer walls [W/(m ² ·K)]	0.25	0.25	0.14	0.16
Roof [W/(m ² ·K)]	0.21	0.31	0.09	0.09
Windows [W/(m ² ·K)]	1.90	1.83	1.00	0.80
Doors [W/(m ² ·K)]	1.00	1.00	1.00	1.00
Infiltration q ₅₀ [m ³ /(h·m ²)]	10.90	5.90	0.80	1.00

RESULTS

The simulations showed that in the future, all four buildings in this study will experience a reduction in their heating energy demand. The two educational buildings with active cooling systems showed increased cooling energy demand, and the two residential buildings without active cooling systems showed increased overheating.

Projected Heating Energy Demand

Figure 6 shows the projected annual heating energy demand [kWh/m² a] for residential buildings under the RCP4.5 and RCP8.5 scenarios combined with the TRY2020, TRY2030, and TRY2050 scenarios, respectively. Figure 7 shows the projected annual heating energy demand for educational buildings under the respective scenarios, expressed in [kWh/m²] to ensure comparability. Simulated heating consumption data for buildings varied from actual consumption data by 0.8% to 6% in the baseline scenario of TRY2020, depending on the building. This level of variation was deemed acceptable, since within the same buildings, the annual energy demand varied by up to 25.5% between the lowest and highest reported energy demand, depending on the winter season severity. Buildings were compared to the TRY2020 baseline weather dataset. For building 1, the decrease in heating energy demand from baseline was 6.2% (2030) and 9.9% (2050) compared to the RCP4.5 scenario, and 7% (2030) and 24% (2050) compared to the RCP8.5 scenario. For building 2, the decreases were 6.8% (2030) and 10.6% (2050) compared to the RCP4.5 scenario, and 7.6% (2030) and 19.2% (2050) in the RCP8.5 scenario. For building 3, the decrease in heating energy demand from baseline was 7.3% (2030) and 11.5% (2050) compared to the RCP4.5 scenario, and 8.2% (2030) and 19.2% (2050) compared to the RCP8.5 scenario. For building 4, the decrease from baseline was 9% (2030) and 14.3% (2050) compared to the RCP4.5 scenario, and 11.9% (2030) and 20.2% (2050) in the RCP8.5 scenario.

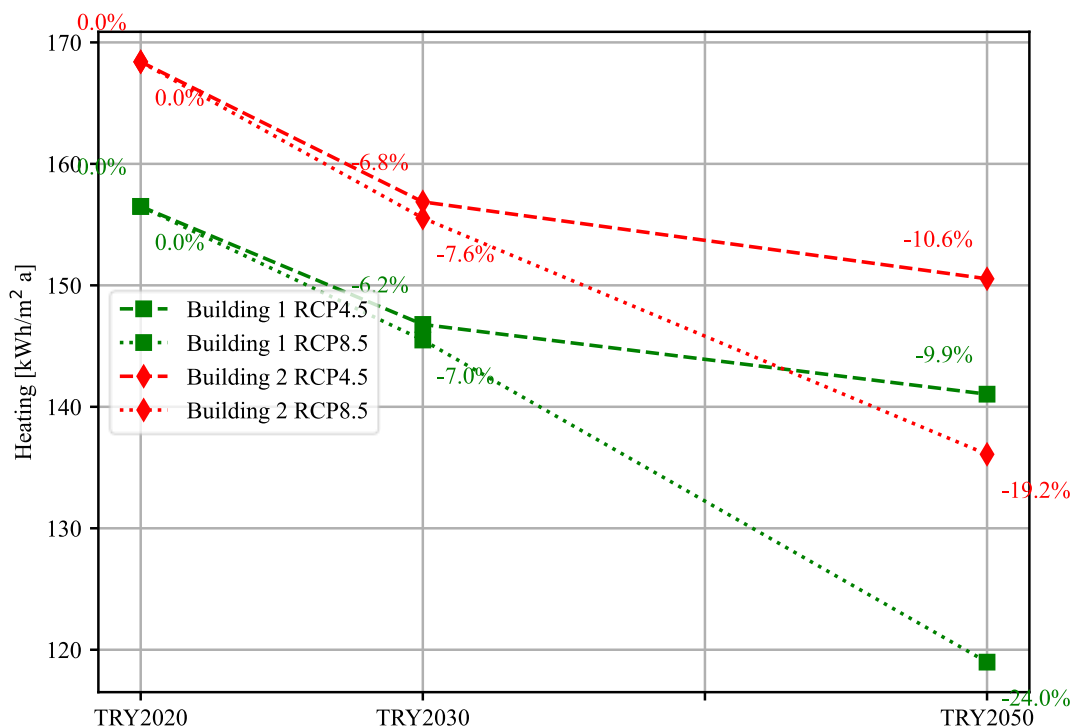


Figure 6. Heating demand of residential buildings

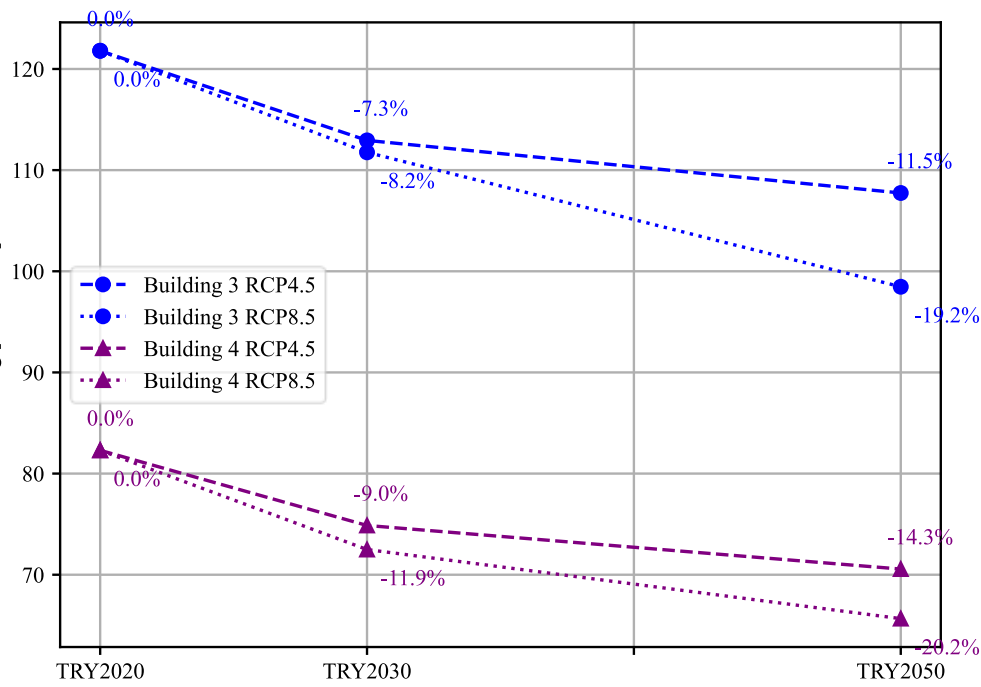


Figure 7. Heating demand of educational buildings

The figures show that the future heating energy demand decreases across all the RCP scenarios and TRYs. As expected, older buildings with MEV consume more energy than the newer ones with MVHR. The energy demand values listed in Table 4 include TRY2020 and two RCP scenarios under TRY2030 and TRY2050.

Table 4. The heating demand change in all buildings

Building	TRY2020 [kWh/m ²]	RCP4.5 2030 [kWh/m ²]	RCP4.5 2050 [kWh/m ²]	RCP8.5 2030 [kWh/m ²]	RCP8.5 2050 [kWh/m ²]
1	156.52	146.78	141.04	145.50	118.89
2	168.39	156.87	150.54	155.54	136.09
3	121.82	112.94	107.74	111.76	98.47
4	82.34	74.87	70.56	72.49	65.66

Projected Cooling Energy Demand

Figure 8 shows the projected annual cooling energy demand [kWh/m² a] for the two educational buildings with pre-installed cooling systems under the RCP4.5 and RCP8.5 scenarios and TRY2020, TRY2030, and TRY2050. The figure shows that future cooling demand increases for all the RCP scenarios and TRYs.

Compared to the baseline, the cooling demand for building 3 increased by 10.2% (2030) and 24.3% (2050) in the RCP4.5 scenario, and by 14.7% (2030) and 44.3% (2050) in the RCP8.5. A similar comparison with building 4 yielded cooling demand increases of 4.4% (2030) and 8.4% (2050) in RCP4.5 and 5.7% (2030) and 14.4% (2050) in RCP8.5. The building 3 cooling system is less effective than the cooling system in building 4, which uses a compression chiller connected to an ambient air heat exchanger in combination with the GSHP for its cooling needs.

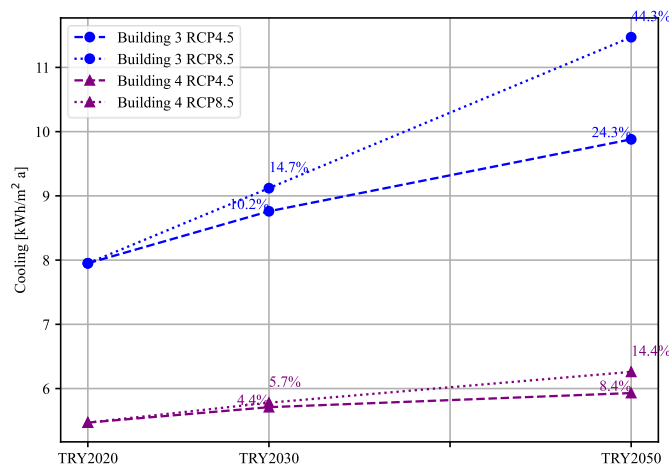


Figure 8. Cooling demand of educational buildings

The values are listed under TRY2020 and each RCP scenario, as well as TRY2030 and TRY2050. When comparing the cooling demand (Table 5) and heating demand changes (Table 4), the cooling demand increases less than the heating demand decreases. The overall energy demand therefore decreases more in each building, even in educational buildings, where additional energy is used for cooling.

Table 5. Cooling demand change in buildings 3 and 4

Building	TRY2020 [kWh/m²]	RCP4.5 2030 [kWh/m²]	RCP4.5 2050 [kWh/m²]	RCP8.5 2030 [kWh/m²]	RCP8.5 2050 [kWh/m²]
3	7.95	8.76	9.88	9.12	11.47
4	5.47	5.71	5.93	5.78	6.26

Overall Energy Demand for Heating and Cooling

For buildings 1 and 2, the final energy demand regarding heating and cooling will remain equal to the heating demand expressed in Figure 6. This is because the buildings do not have additional cooling energy demand in the future, as they were modelled and simulated as they are (without cooling systems).

For building 3 the overall energy demand was 129.8 kWh/m² in TRY2020. In RCP4.5, the consumption was 121.7 kWh/m² (2030) and 117.6 kWh/m² (2050). In RCP8.5, the consumption was 120.88 kWh/m² (2030) and 109.9 kWh/m² (2050). For building 4, the overall energy demand for TRY2020 was 87.8 kWh/m², and in RCP4.5, 80.6 kWh/m² (2030) and 76.5 kWh/m² (2050). In RCP8.5, overall energy demand was 78.3 kWh/m² (2030) and 71.9 kWh/m² (2050).

Projected Overheating

Similarly, the overheating follows the same trends as the previous two phenomena. In the future, if a weather increase is observed, for the hours exceeding the setpoints: 27 °C in the case of block-of-flats, and 25 °C in the case of educational buildings. Figure 9 shows the percentage of overheating zones for the two residential buildings: building 1 (133 zones) and building 2 (141 zones).

Building 1 was already overheating by 82% in the baseline TRY2020 scenario and continued to overheat further to 85.7% in scenario RCP4.5-TRY2030 and to 87.2% in scenario RCP4.5-TRY2050. In scenario RCP8.5-TRY2030, building 1 overheated to 86.5%, and in scenario RCP8.5-TRY2050 to 97.0%.

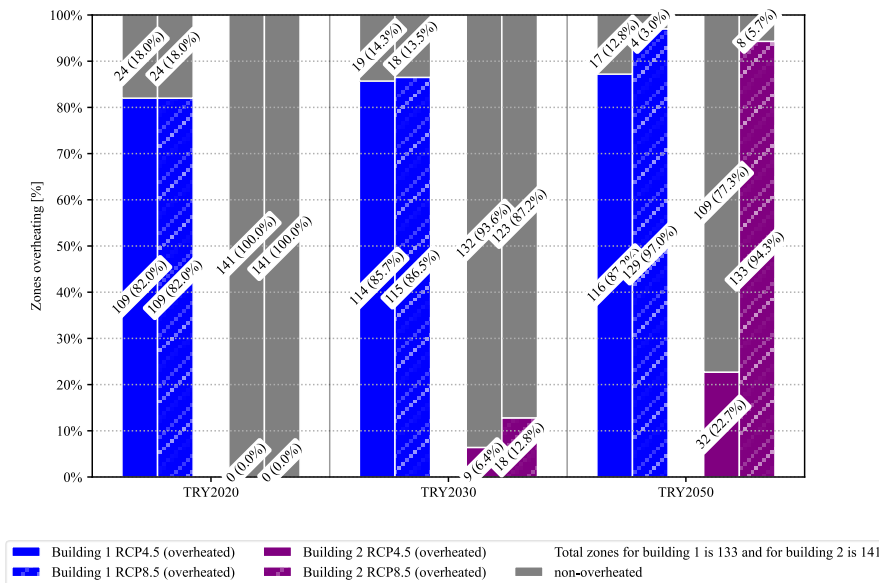


Figure 9. Number of zones overheating as % of total zones in residential buildings

Building 2 is not overheating in the baseline scenario TRY2020. In scenario RCP4.5-TRY2030, it overheats by 6.4% and in scenario RCP4.5-TRY2050, it continues to overheat to 22.7%. In scenario RCP8.5-TRY2030, building 2 overheats by 12.8% and in scenario RCP8.5-TRY2050 to 94.3%.

Figure 10 shows the percentage of overheating zones of the two educational buildings: building 3 (37 zones) and building 4 (68 zones). Building 3 is not overheating in the baseline scenario TRY2020. In the RCP4.5-TRY2030 scenario, it overheats by 8.1% and in RCP4.5-TRY2050, it continues to overheat to 13.5%. In scenario RCP8.5-TRY2030, building 3 overheats by 8.1% and in scenario RCP8.5-TRY2050 to 27.3%. This overheating, even with cooling systems present, is attributed to a cooling system designed without considering future changing weather conditions. Building 4 did not overheat in either the baseline scenario TRY2020 or any future weather scenarios.

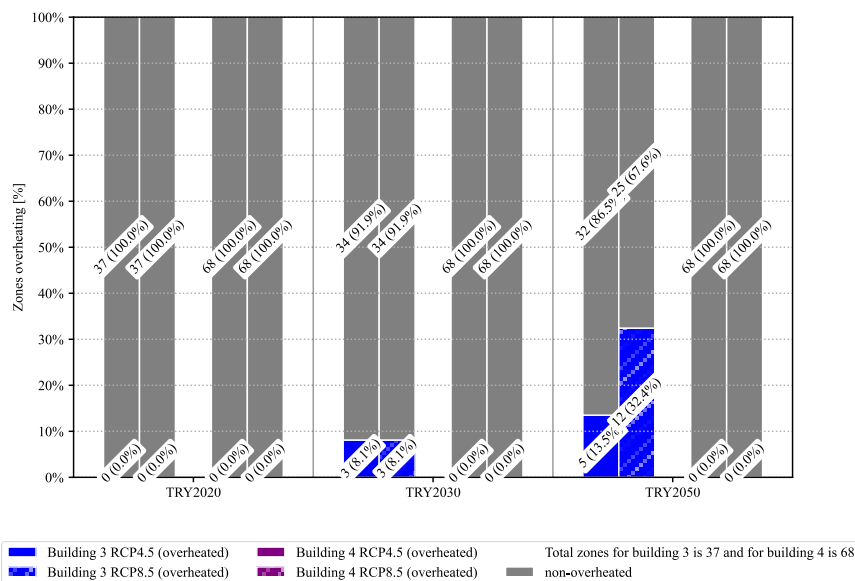


Figure 10. Number of zones overheating as % of total zones in educational buildings

DISCUSSION

Summing up, older residential multi-storey apartment buildings are prone to overheating, with some buildings already overheating under the current weather scenario TRY2020, as exhibited in building 1. Generally, in older residential buildings, overheating increases severely, especially in the RCP8.5-TRY2050 scenario, as shown in [Figure 9](#). The projected overheating results indicate that it is necessary to investigate the potential of passive and active low-emission cooling solutions for older buildings, lacking cooling systems, as proposed by the EU [16]. A limitation of our study is that we used only four buildings (two residential and two educational). These particular buildings were selected because modelling and simulation with IDA ICE require very exact data, which were available to us from these buildings. The four selected buildings vary by building use type, age, occupation periods, structural characteristics, and technical systems. In addition, the Kanta-Häme region serves as a representative sample of the Finnish building stock because it is located in southern Finland, where population density and building concentration are highest. Therefore, it is considered indicative of the overall characteristics of buildings throughout Finland and other similar subarctic regions. The results of our simulations showed similar trends in heating and cooling demand across all building types. All four selected buildings were typical Finnish buildings, designed and modelled according to the design values of the Finnish building code and the weather data from the FMI; hence, they represent a satisfactory sample of the Finnish building stock. Other building types, such as office spaces, operate on similar temporal cycles as educational buildings, and therefore can be assumed to have similar energy demand projections. Other types of non-residential buildings, such as warehouses and swimming halls, offer limited value for analysing energy demand projections. Hospitals are an exception among non-residential building types, but their unique energy-use patterns require a level of detailed examination not available to the public due to their status as critical infrastructure. The four selected buildings provide a clear overview of how energy demand in the Finnish building stock responds to changing climate conditions.

The results provided answers to the main research question of this study, namely “How does the changing future climate affect buildings’ energy demand in the Kanta-Häme region and subsequently in Finland and similar subarctic regions?”

The results confirmed the hypotheses of the study:

H1: The building stock in Finland will face increased cooling energy demand in the future.

H2: The overall annual energy demand of buildings in Finland will decline in the future.

CONCLUSION

The prevailing green shift in energy production requires research on the energy demand of different ages and types of buildings. This study aimed to assess the impact of future climate change on building energy demand in the Kanta-Häme area of Finland. This study utilised the Kanta-Häme region as a representative context to investigate and project the impacts of climate change in Finland and similar subarctic regions. The research methodology was grounded in the application of the Finnish building code alongside meteorological data sourced from Finland. It is important to note that building regulations and climatic conditions in other subarctic regions may differ from those in Finland, potentially influencing the generalisability of the findings to other settings. Simulation results showed that under the RCP4.5 and RCP8.5 scenarios in TRY2030 and TRY2050, the heating energy demand decreased for all four simulated buildings. The cooling energy demand increased for educational buildings with pre-installed cooling systems.

The residential buildings without pre-installed cooling systems showed signs of overheating. Depending on the scenario, the overall energy demand in residential buildings decreased from -6.2% to -24% and in educational buildings from -6.2% to -18% . The results from the overheating assessment showed that building 1 was already overheating by 82% in the baseline scenario and continued to overheat to 97.0% in the worst-case scenario. Building 2 did

not overheat in the baseline scenario, but it overheated by 6.4% in the best-case scenario, and by up to 94.3% in the worst-case scenario. Building 3 did not overheat in the baseline scenario; it overheated moderately due to its existing cooling system, reaching 8.1% in the best-case scenario and up to 27.3% in the worst-case scenario. Building 4 did not overheat in the baseline scenario nor in any future weather scenarios. The main challenge, which will require innovative, climate-friendly and energy-efficient heat-mitigating solutions, will concern existing buildings, particularly those without cooling systems. This study investigated four buildings in the Kanta-Häme region, a novel approach regarding future climate projections in the region. The aim was to deepen understanding of the effects of climate change on the building stock in the region, and subsequently, in Finland and similar subarctic regions. The main results showed that global warming leads to reduced heating demand and increased cooling demand in Kanta-Häme, Finland. Similar findings from other areas in Finland confirmed our results, enabling generalisation to Finland and other similar subarctic regions.

Finnish building regulations are evolving due to climate change and stricter EU requirements, such as the Energy Performance of Buildings Directive (EPBD), to include clearer rules on managing summer temperatures and the need for cooling in new buildings. Cooling is becoming standard under national regulations, covering both passive and active solutions, in response to increased heatwaves and the need for living comfort and energy efficiency. Further work will focus on innovative and passive cooling solutions to support regional stakeholders in preparing their mitigation and adaptation actions to minimise future overheating risks.

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NOMENCLATURE

Symbols

A	area	$[m^2]$
E	energy	$[MWh]$
E_a	specific energy per area	$[kWh/m^2]$
E_s	specific annual energy demand	$[kWh/(m^2 a)]$
L	length	$[m], [mm]$
P	power	$[kW]$
q_{50}	infiltration	$[m^3/(h \cdot m^2)]$
q_r	radiative heat flux	$[W/m^2]$
T	temperature	$[^{\circ}C]$
$U\text{-value}$	thermal transmittance	$[W/(m^2 \cdot K)]$

Greek letters

η	efficiency	$[\%]$
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Abbreviations

2D	Two Dimensional
3D	Three Dimensional
ABM	Agent-Based Modelling
AHU	Air Handling Unit
CAD	Computer-Aided Design
COP	Coefficient of Performance

DH	District Heating
DHW	Domestic Hot Water
EU	European Union
FMI	Finnish Meteorological Institute
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HX	Heat Exchanger
HVAC	Heating, Ventilation, and Air Conditioning
IDA-ICE	IDA Indoor Climate and Energy
IFC	Industry Foundation Classes
IPCC	Intergovernmental Panel on Climate Change
MEV	Mechanical Extraction Ventilation
MVHR	Mechanical Ventilation with Heat Recovery
nZEB	Nearly-Zero Energy Buildings
R	Radiator
RCP	Representative Concentration Pathway
RF	Radiative Forcing
TRY	Test Reference Years
UFH	Underfloor Heating

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