Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2026, Volume 14, Issue 3, 1140712

Original Research Article

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

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Cite as: Siakas, D., Vassallo, O., Galassini, M., Kontu, K., Impact of Future Changing Climate on the Energy Demand of Finland's Building Stock, J.sustain. dev. energy water environ. syst., 14(3), 1140712, 2026, DOI: https://doi.org/10.13044/j.sdewes.d14.0712

## 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 the buildings the heating energy demand change 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% depending on climate scenario and cooling technique. This indicates 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 elevate the need for cooling to prevent overheating, mitigate discomfort and associated health risks, particularly among vulnerable populations. The main challenge, concern existing buildings, particularly the ones 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 with increasing heat wave occurrences [1]. Climate scientists have repeatedly warned governments for devastating future extreme weather consequences if we do not seriously commit to mitigation and adaption actions [2]. As a response to this, 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, the temperature in Finland 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 "Representative Concentration Pathway (RCP)" climate scenarios.

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They highlighted that the building sector is facing environmental, technical, economic, and social challenges due to a warming climate. The increasing overheating during summers requires solutions to mitigate building occupant discomfort.

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 makes it a key focus area in the drive to decrease energy use and GHG emissions. The building sector is projected to significantly contribute to the acceleration for reaching the EU's GHG target of 55% reduction by 2030 compared to 1990 levels and climate neutrality by 2050 [3]. At 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 (nZEB). National building codes vary according to the respective 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] emphasize that building codes constitute a successful policy tool for lowering energy use in buildings. Considering that 85% of buildings in the EU were constructed before the year 2000, and 75% of them exhibit poor energy performance [3], which indicates that greater emphasis should be placed on renovation efforts to reduce emissions. Ruosteenoja & Jylhä [4] articulate the importance for preparing and adapting the building sector to a 2.0°C increase in global temperatures.

There is evidence to support the belief of mortality rates increasing during heatwaves. This has been confirmed by the World Health Organization (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 healthy indoor environment in the future [13]. Decrees set 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 the global temperatures increase, the need for cooling energy will subsequently increase, which is already visible in near future scenarios. Increased cooling demands in buildings worldwide is attributed to global warming, change in demographics (population growth, urbanization, aging population vulnerable to elevated heat levels) and economic growth (increased living standards) [16]. Increased use of active cooling systems impact significantly on the overall energy demand as regards to energy provisions and emissions. A report by the "International Energy Agency" (IEA) highlights that energy demand regarding space cooling accounts for approximately 20% of the total energy consumed by buildings worldwide [17]. Combining passive strategies with low-emission active cooling methods are recommended by the EU [16]. Solutions that utilize contemporary design approaches encouraging passive cooling strategies, such as effective insulation, natural ventilation, shading and thermal mass, can significantly decrease the reliance on active cooling systems that depend on external energy sources, such as electricity. Passive cooling methods are increasingly utilized 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 by using IDA ICE simulations. The simulations showed improved visual comfort, daylight availability, and reduction of 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 simulations make it possible to evaluate energy use and occupant comfort while identifying opportunities to reduce energy demand and GHG emissions [21]. Research regarding optimization of heating, ventilation, and air conditioning (HVAC) systems for improving efficiency and minimizing 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 environment quality, energy consumption, and the future climate resilience of a building located in the Tampere region of Finland. Simulation models for the case building were developed both before and after the implementation of the energy retrofit. Wilk-Słomka et al. [24] used ESP-r to simulate one low-energy building in Poland and found that the building will require additional active cooling in the 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 in China. They simulated energy demand of 4754 buildings in Harbin, China, under complex behavioural conditions.

Nevertheless, there is limited research that addresses climate change impacts on the energy demand of Finland's building stock. Some studies have been performed in other regions in Finland, such as in Tampere [23] and in Helsinki [13]. Kanta-Häme region was chosen due to funding for research regarding the effect of future weather conditions on the building stock in the area, and 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 within the Kanta-Häme region, regarding future climate projections. The aim is to deepen the understanding of effects of climate change to the building stock in the region, and subsequently in Finland and similar subarctic regions. In addition, the aim is to support the regional stakeholders to understand the future challenges and prepare their mitigation and adaption 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 for improving understanding and awareness about causes and effects of climate change, and for understanding what proactive mitigation measures can be taken. The "Intergovernmental Panel on Climate Change" (IPCC) serves as a driving force in the development of various future emission projection scenarios. Future scenarios are used for investigating the impact of future climate change on the eco-systems and the impact of 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 8.5W/m². These scenarios were developed using different assumptions for the period 1850–2100 concerning energy use and emissions, including increases in $CO_2$ concentrations, temperature, and changes in precipitation patterns [27]. In this study, RCP4.5 and RCP8.5, commonly used in building energy simulations, are applied as future climate projection datasets for the building simulations.

RCP4.5 represents a stabilization scenario in which radiative forcing reaches 4.5W/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, $CO_2$ 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].

The reason why RCP4.5 and RCP8.5 are commonly used in building energy simulations is 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, the decree 1009/2017 from the "Ministry of the Environment" of Finland establishes the heating limits during planning and building of new buildings [15]. These 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 applied to all new buildings, and 545/2015 is in effect for all dwellings and other living quarters.

Additional factors, including ventilation in living spaces and indoor $CO_2$ concentration, should be considered when designing healthy residential environments. According to Decree 545/2015, a minimum ventilation rate of 0.35dm$^3$/s per square metre is required in all dwellings during the occupied periods [14]. Furthermore, the decree establishes a threshold of 2100 mg/m$^3$ (or 1150ppm) higher than the outdoor $CO_2$ concentration, beyond which mitigation measures should be implemented.

## SIMULATION ENVIRONMENT

Simulations for 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 the indoor climate and the energy demand of a building. IDA ICE simulation tool has been used in previous research work concentrating 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, which allow precise modelling of temperature and energy flows. It has solvers, which are capable of iterative resolution of nonlinear equations, adaptive time stepping for accuracy during fast-changing conditions and component-based equation solving. The tool computes design heating load, cooling load (peak and time based), zone-level and system-level energy flows. It is a full-year energy simulation tool, including space heating and cooling demand, domestic hot water (DHW) demand, fan/pump electricity, lighting and internal gain, system losses, and primary energy (and $CO_2$ 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.

From the present and future weather scenarios as shown in Figure 1 the projected heating and cooling energy demand changes were examined. Four buildings were studied, three of them with actual energy demand data, which was crucial in verifying the results from IDA ICE. The buildings selected for simulation purposes are residential and educational buildings, with different building materials and construction years. Future weather scenarios were analysed to assess how energy consumption and indoor climate conditions may evolve over time. All study cases were first simulated in the current weather scenario TRY2020 and then compared to 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.

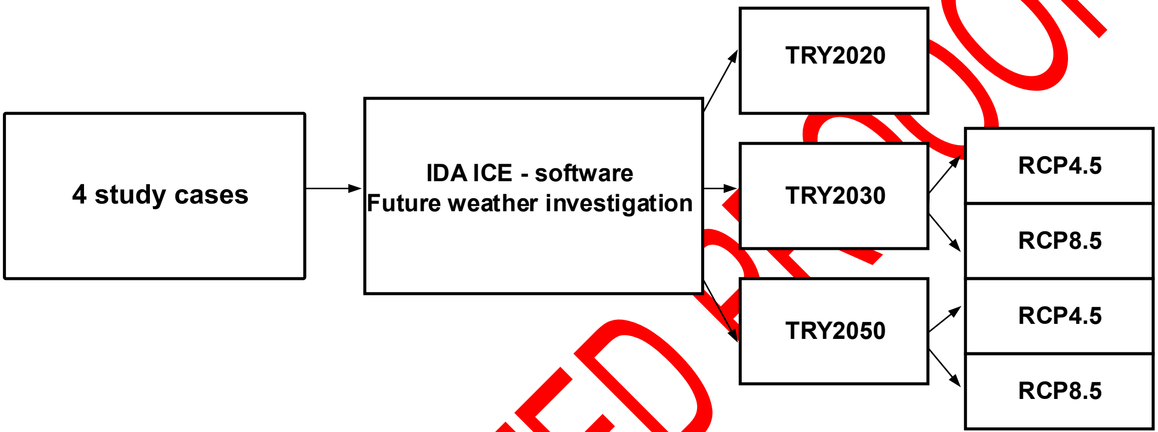


Figure 1. Scenarios generated for building simulation with weather data from FMI

## Study cases

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

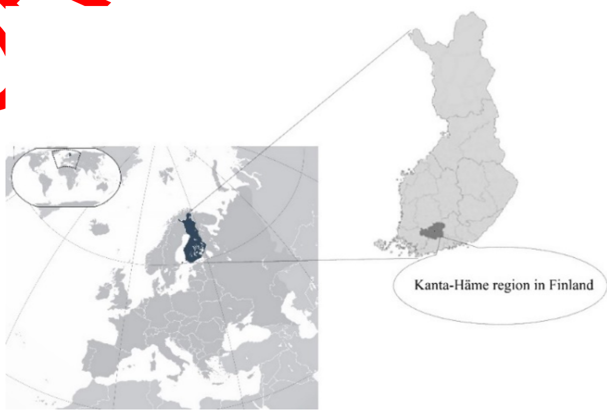


Figure 2. Kanta-Häme region

## Residential buildings

The study included two residential blocks of flats built in the 1950s and in 1990s respectively. They are both connected to the district heating (DH) which is used to warm up spaces through 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 modification affecting the envelope structures. This information was the basis for the U-value selections made when creating a model in the IDA ICE software.

The newer building 2 is still in its original condition, with only a few bathrooms being 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 being 9 floors tall with a relatively small building footprint, whereas the newer one is made up of three floors and with a significantly larger building footprint. The first one has a tower-like shape, whereas the second one has an L-shape. Figure 3 shows the 3D models created in IDA ICE of the two buildings, including their orientations.

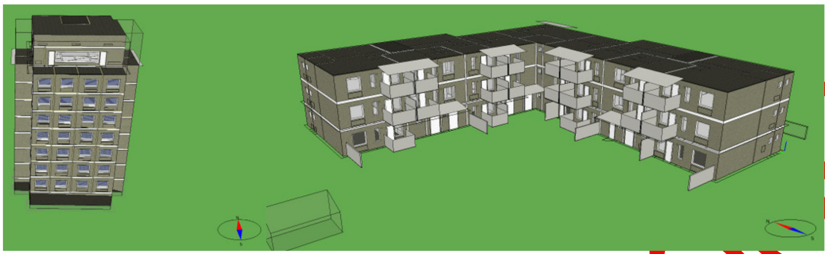

Figure 3. 3D models of building 1(left) and building 2 (right) in IDA ICE software

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

Both buildings come with window blinds installed in the gap between the inner glass and the outer one. Window blinds are an effective method to prevent the sun radiation from entering the building, mitigating overheating in the cooling season.

The two residential buildings were first simulated in the current weather scenario TRY2020 for comparison and to make sure 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 for 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 in current weather conditions, probably due to the lack of shading elements (for instance balconies) and the geometry properties, the south facing façade is mostly covered by windows. The building is connected to the DH line, and the heat is distributed to the spaces through water circulating radiators (R). Actual consumption data of building 1 was 270MWh, with TRY2020 simulated data yielding 285MWh (variation +6% from 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. Similarly to building 1, the heating system is DH with radiators as distribution method. Actual consumption data of building 2 varied between years, due to varying winter severity between years, effecting the heating season energy demand, from 223 to 280MWh (up to 25.5% variation in real-life consumption data). Simulated consumption data in TRY2020 was about 284MWh (+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 | ling 4 |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Floor slab | Towards heated space:<br>Linoleum sheet (plastic floor covering) 5mm<br>Lightweight concrete 20mm<br>Air gap 50mm<br>Lightweight concrete 170mm.<br>Slab towards ground (before basement, warm space):<br>Linoleum sheet 50mm<br>Lightweight concrete 20mm<br>Concrete 200mm<br>Expanded polystyrene board 207mm.<br>Towards unheated space:<br>Lightweight concrete 20mm<br>Concrete 100mm<br>Wood-wool board 150mm<br>Concrete 150mm<br>Sand 200mm<br>Natural subsoil 150mm. | Render mortar 5mm<br>Concrete 265mm<br>Expanded polystyrene board 130mm<br>Ventilated air cavity 50mm<br>Sand 50mm<br>Acrylic sheet 20mm<br>Soil 200mm. | Towards unheated space:<br>Linoleum sheet flooring 2mm<br>Lightweight concrete 80mm<br>Mineral wool board (heavy) 200mm<br>Expanded clay aggregate (LECA) 300mm.<br>Towards heated space:<br>Lightweight linoleum flooring 5mm<br>Lightweight concrete 20mm<br>Concrete 200mm<br>Expanded polystyrene board 207mm. | Towards heated space:<br>1) Linoleum sheet 15mm<br>Lightweight concrete 80mm<br>Hollow-core concrete slab 320mm<br>2) Linoleum sheet 10mm<br>Lightweight concrete 80mm<br>Hollow-core Slab 320mm<br>Towards unheated space:<br>Linoleum sheet 15mm<br>Lightweight concrete 80mm<br>Hollow-core concrete slab 320mm<br>Polyurethane insulation plates 170mm<br>Ventilated air cavity 1500mm<br>Coarse gravel 200mm<br>Plastic film 0.2mm |
| External walls | Render mortar 10mm<br>Concrete 150mm<br>Mineral wool 150mm<br>Ventilated air gap 70mm<br>Lightweight concrete blocks 100mm<br>Render mortar 10mm | Concrete 80mm<br>Mineral wool 150mm<br>Lightweight concrete blocks 80mm<br>Render mortar 5mm | Gypsym board 13mm<br>Wood-fibre board 48mm<br>Polyamide film 1mm<br>Framed structure cc600 with insulation 198mm<br>Wood-fibre board (wind barrier) 90mm<br>Air gap 48mm<br>Wood 23mm | 1) Render mortar 10mm<br>Concrete 150mm<br>Polyurethane insulation plates 150mm<br>Ventilated air gap 157mm<br>Cement-based chipboard 8mm<br>2) Render mortar 10mm<br>Concrete 300mm<br>Polyurethane insulation plates 150mm<br>Ventilated air gap 157mm<br>Cement-based chipboard 8mm<br>3) Paroc Panel 265mm<br>Ventilated air gap 57mm<br>Cement-based chipboard 8mm |
| Roof / Upper slab | Render mortar 10mm<br>Concrete 90mm<br>Mineral wool 180mm | Drywall 13mm<br>Concrete 200mm<br>Mineral wool 200mm | Bitumen membrane 10mm<br>Mineral wool board (heavy) 486mm<br>Concrete 150mm<br>Render mortar 10mm | Bitumen membrane 10mm<br>CLT board 25mm<br>Ventilated air gap 150mm<br>Windproof rock wool insulation 50mm<br>Rock wool insulation 400mm<br>CLT board 25mm |

**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, a kitchen and office rooms for the staff. The building has a floor area of 887 m$^2$ and it has a timber structure for outside walls and roof, whereas the floor is a concrete slab on ground. The heating demand of the building is handled through 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, which provides cooling via the central air handling unit. The kindergarten has 18 photovoltaic solar panels on the south-facing roof that each year produce 2138kWh, according to simulation. Figure 4 shows the 3D model of the building in IDA ICE software. Actual consumption data from building 3 was 107MWh and simulated data was about 107.9MWh (+0.8% from actual data).

Figure 4. 3D model of the 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, hosting a degree programme in food engineering and biotechnology as well as activities within the Smart-Bio key ecosystem. The building is 13m high and comprises of two floors and an attic, with a total net floor area of 2,156m². 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 data in TRY2020 was 209.0MWh

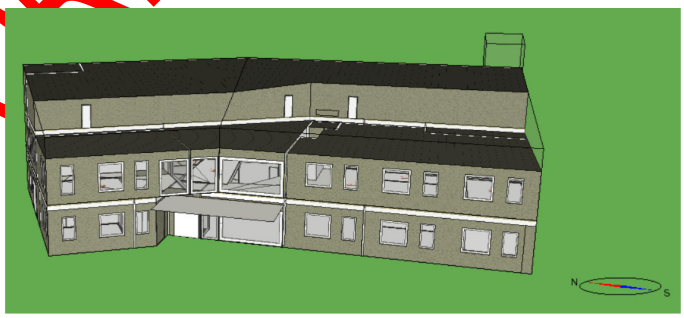

Figure 5. 3D view of building 4 in IDA ICE software

The building's heating and cooling demands are managed by its building plant. The system features a GSHP with a capacity of 10kW and a coefficient of performance (COP) of 4, supported by six 330-meter-deep boreholes and a DH top-up source. Two thermal storage tanks, each with a capacity of 1m³, store hot and cold water separately. For cooling, a 10kW 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. The space heating is done mainly with waterborne UFH, except of five spaces that are heated with waterborne radiators. The ventilation system consists of four AHUs. Three of them have cross flow plate heat exchangers (HX) and night flush ventilation control and one 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 summarized in Table 2. The table also includes occupation ratio (hours of the day divided by days of the week). Occupation ratio is used in the simulation tool to determine the impact of the usage of the building, 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 | Occupation ratio [hours/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 are built in different years and have different heating systems. General information regarding the buildings U-values and air leakage ($q_{50}$) 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. Minimizing U-values decrease the heat transfer rates between building components and therefore also heat demand. Building orientation (moving large windows from south and west facades to north) decrease the cooling energy demand, theoretically [36]. Modelling was limited to real-life buildings and therefore changes to these components are out of scope of this study.

Table 3. U-value and infiltration values 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 q50 [ $m^3$/hr·$m^2$ ] | 10.90 | 5.90 | 0.80 | 1.00 |

## RESULTS

The results of the simulations showed that in the future all four buildings in this study will phase a reduction in their heating energy demand. The two educational buildings, that have active cooling systems in place, showed a rise in their cooling energy demand and the two residential buildings, that lack active cooling systems, showed an increased overheating.

### Projected heating energy demand

Figure 6 shows the projected annual heating energy demand in (kWh/$m^2$ a) for residential buildings under RCP4.5 and RCP8.5 scenarios and TRY2020, TRY2030 and TRY2050 respectively. Figure 7 shows the projected annual heating energy demand for educational buildings under the respective scenarios. kWh/m2 a was chosen so that the results can be comparable. Buildings' simulated heating consumption data varied from actual consumption data depending on building by 0.8% up to 6% in the baseline scenario of TRY2020. This level of variation was deemed acceptable, since within same buildings the annual energy demand varied up to 25.5% from lowest reported energy demand to highest reported energy demand, depending on the winter season severity. Buildings were compared to TRY2020 baseline weather dataset. For building 1 the decrease in heating energy demand from baseline was 6.2% (2030) and 9.9% (2050) when comparing to the RCP4.5 scenario, and 7% (2030) and 24% (2050) when comparing to the RCP8.5 scenario. For building 2 the decrease was 6.8% (2030) and 10.6% (2050) when comparing to the RCP4.5 scenario, and 7.6% (2030) and 19.2% (2050) in RCP8.5 scenario. For building 3 the decrease in heating energy demand from baseline was 7.3% (2030) and 11.5% (2050) when comparing to the RCP4.5 scenario, and 8.2% (2030) and 19.2% (2050) when comparing to the RCP8.5 scenario. For building 4 the decrease from baseline was 9% (2030) and 14.3% (2050) when comparing to the RCP4.5 scenario, and 11.9% (2030) and 20.2% (2050) in RCP8.5 scenario.

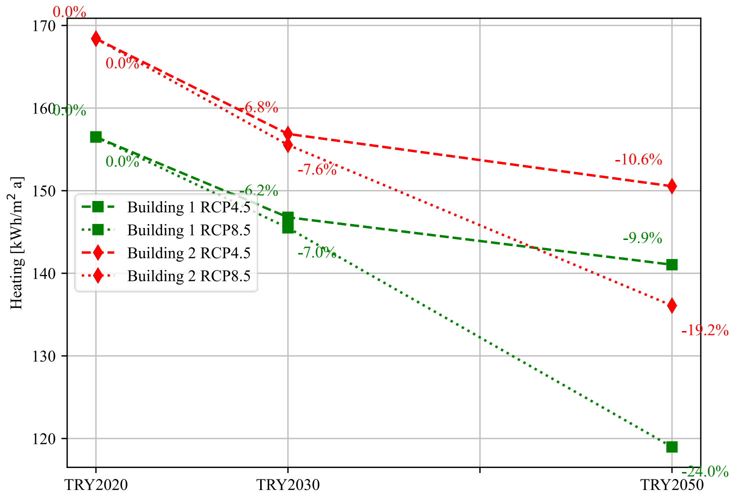


Figure 6. Heating demand of residential buildings

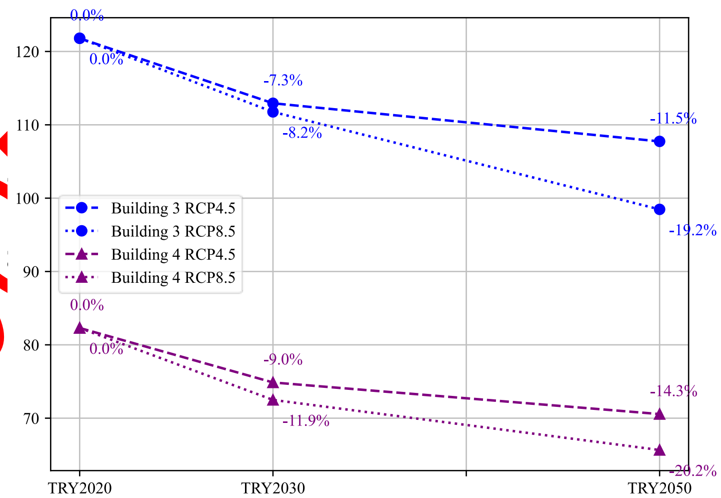


Figure 7. Heating demand of educational buildings

The figures show that the future heating energy demand decreases for all the RCP scenarios and TRYs. As expected, the older buildings with MEV consume more energy than the newer ones with MVHR. Table 3. Heating demand change in buildings 1 and 2

The values are listed in Table 4 as well in TRY2020 and in each RCP scenario under TRY 2030 and TRY2050

Table 4. Heating demand change in all the buildings

| Building | TRY2020 [kWh/m2] | RCP4.5 2030 [kWh/m2] | RCP4.5 2050 [kWh/m2] | RCP8.5 2030 [kWh/m2] | RCP8.5 2050 [kWh/m2] |
|---|---|---|---|---|---|
| 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 in (kWh/m$^2$ a) for the two educational buildings with cooling systems preinstalled, under RCP4.5 and RCP8.5 scenarios and TRY2020, TRY2030 and TRY2050 respectively. The figure shows that the future cooling energy 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 RCP4.5 scenario, and by 14.7% (2030) and 44.3% (2050) in RCP8.5. Similar comparison with building 4 yielded cooling demand increase of 4.4% (2030) and 8.4% (2050) in RCP4.5 and 5.7% (2030) and 14.4% (2050). The building 3 cooling system is less effective compared to the cooling system of building 4 that uses a compression chiller connected to an ambient air heat exchanger in combination with the GSHP for its cooling needs.

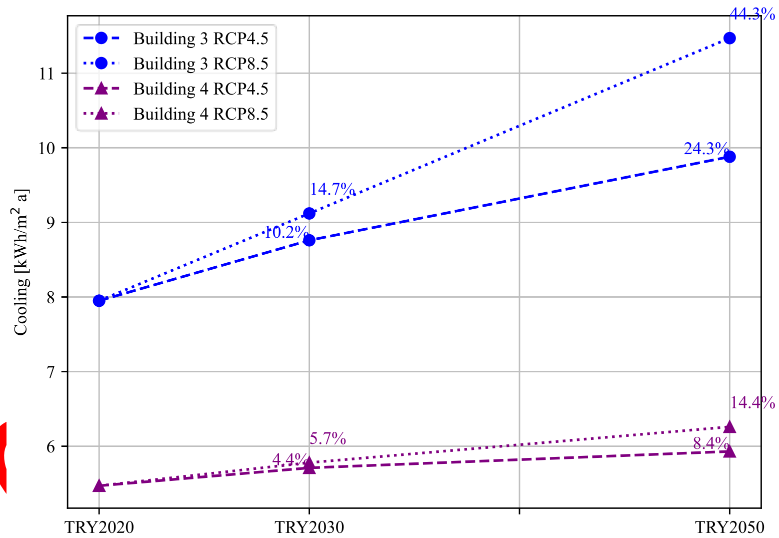


Figure 8. Cooling demand of educational buildings

The values are listed in as well under TRY2020 and each RCP scenario in TRY2030 and TRY2050. When comparing the cooling demand (Table 5) and heating demand changes (Table 4), cooling demand increases less than the heating demand decreases. The overall energy demand therefore decreases more in each building, even in the educational buildings, where there is additional energy 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 regarding 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 due to the fact that the buildings do not have additional cooling energy demand even in the future, as the buildings were modelled and simulated as they were (without cooling systems).

For building 3 the overall energy demand was 129.8kWh/m$^2$ in TRY2020. In RCP4.5 the consumption was 121.7kWh/m$^2$ (2030) and 117.6kWh/m$^2$ (2050). In RCP8.5 the consumption was 120.88kWh/m$^2$ (2030) and 109.9kWh/m$^2$ (2050). For building 4 the overall energy demand for TRY2020 was 87.8kWh/m$^2$, and in RCP4.5 80.6kWh/m$^2$ (2030) and 76.5kWh/m$^2$ (2050). In RCP8.5 overall energy demand was 78.3kWh/m$^2$ (2030) and 71.9kWh/m$^2$ (2050).

### Projected overheating

Similarly, the overheating is following the same trends as the previous two phenomena. In the future weather an 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 of the two residential buildings, building 1 (total number of zones 133) and building 2 (total number of zones 141).

*Building 1* was overheating already in the baseline TRY2020 scenario by 82% and continue to further overheat 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%.

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

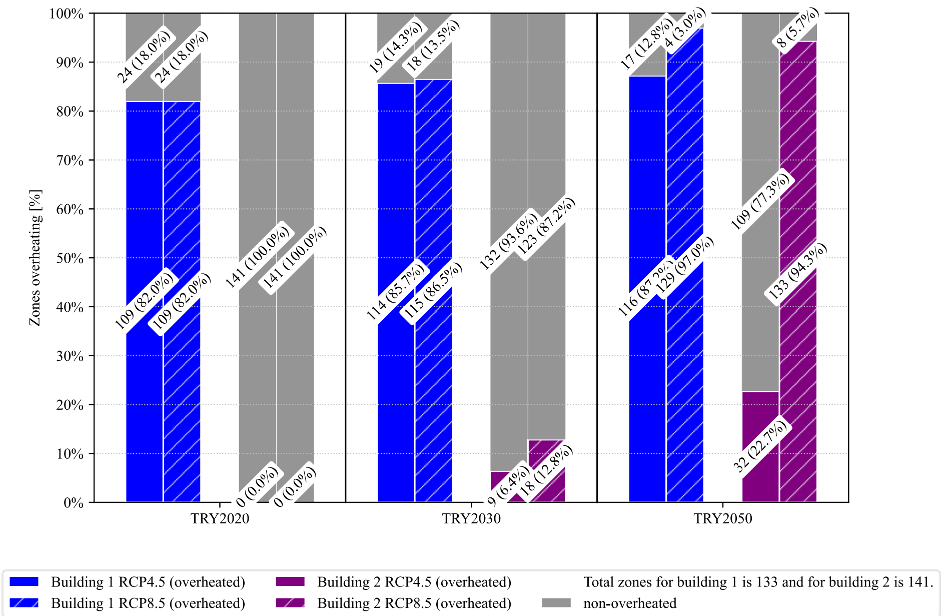


Figure 9. Numbers of zones overheating as % of total zones overheating in residential buildings

Figure 10 shows the percentage of overheating zones of the two educational buildings, building 3 (total number of zones 37) and building 4 (total number of zones 68).

*Building 3* is not overheating in the baseline scenario TRY2020. In scenario RCP4.5-TRY2030 it overheats by 8.1% and continue to overheat up to 13.5% in scenario RCP4.5-TRY2050 In scenario RCP8.5-TRY2030 building 3 overheats by 8.1% and in scenario RCP8.5-TRY2050 to 27.3%. This overheating, even if cooling systems are present, is attributed to fact that the cooling system design did not consider the future changing weather conditions.

*Building 4* did not overheat neither in the baseline scenario TRY2020 nor in any future weather scenarios.

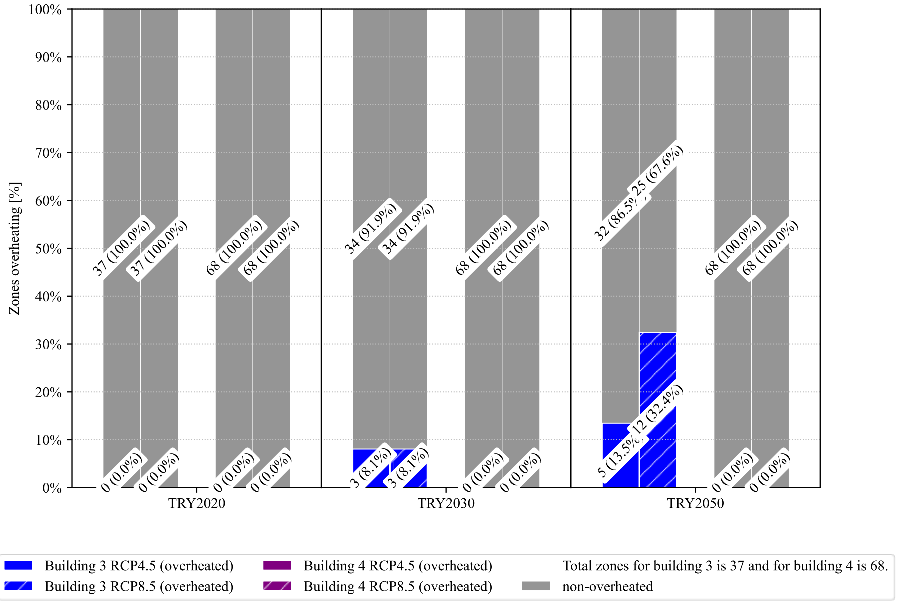


Figure 10. Numbers of zones overheating as % of total zones overheating in educational buildings

## DISCUSSION

Concluding, it can be said that older residential multi-storey apartment buildings are prone to overheating, with some buildings overheating already on the current weather scenario TRY2020, as exhibited in building 1. Generally, in older residential buildings the 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 in our study is that we used only four buildings (two residential and two educational buildings). These particular buildings were selected because modelling and simulation with IDA ICE require very exact data, that was 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 due to its location 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 from our simulations showed similar trends regarding heating and cooling demand for all buildings regardless of type. All the four selected buildings were typical Finnish buildings, designed and modelled according to the design values from the Finnish building code and the weather 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, like warehouses and swimming halls, offer limited value when analysing energy demand projections. Hospitals are an exception among the non-residential building types, but their unique patterns of energy use 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. The aim of this study was to assess the impact of future climate change on the energy demand of buildings 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, which could influence the generalisability of the findings to other settings. Simulation results showed that under scenarios RCP4.5 and RCP8.5 in TRY2030 and TRY2050 the heating energy demand decreased for all the four simulated buildings. The cooling energy demand increased for the educational buildings that had cooling systems pre-installed. The residential buildings that did not have cooling systems pre-installed 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 the building 1 was overheating already in the baseline scenario by 82% and continued to further overheat up to 97.0% in the worst case scenario. Building 2 did not overheat in the baseline scenario but overheated by 6.4% in the best-case scenario and up to 94.3% in the worst. Building 3 did not either overheat in the baseline scenario, it overheated moderately, due to is existing cooling system, reaching 8.1% in the best-case scenario and up to 27.3% in the worst scenario. Building 4 did not overheat neither in the baseline scenario nor in any future weather scenarios. The main challenge, that will require innovative, climate-friendly and energy-efficient heat mitigating solutions, will concern existing buildings, particularly the ones 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 the understanding of effects of climate change to 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 e.g. by Farahani [37], Jylhä et al. [38], Sukanen et al. [39] and Pulkkinen et al. [6]; [40], confirmed our results for generalising them 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) [3], 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 [41]. Further work will concentrate on innovative and passive cooling solutions for supporting the regional stakeholders to prepare their mitigation and adaption actions to minimise future overheating risks.

## ACKNOWLEGEMENTS

We want to thank the “Adapting the built environment of Kanta-Häme to climate change (ILMARA) project” for giving us the opportunity to investigate Kanta-Häme regions building stock regarding future weather scenarios. The ILMARA project is founded by the European Union and the Regional Council of Kanta-Häme.

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