Design strategies to minimise heating and cooling demands for passive houses under changing climate

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Abstract

In this study, we analyse the heating and cooling demands of a multi-storey residential building version, designed to the passive house criteria in Southern Sweden and explore various design strategies to minimise these demands under different climate change scenarios. The analysis is performed for recent (1996–2005) and future climate periods of 2050–2059 and 2090–2099 based on the Representative Concentration Pathway scenarios, downscaled to conditions in South of Sweden. Design strategies include efficient household equipment and technical installations, bypass of ventilation heat recovery unit, window solar shading, building orientation, window size and properties, besides mechanical cooling. Results show that space heating demand reduces, while cooling demand increases as the risk of overheating under the future climate scenarios. The most important design strategies are efficient household equipment and technical installations, solar shading, bypass of ventilation heat recovery unit and window u-values and g-values. Total annual final energy demand decreased by 40–51 % and overheating is avoided or significantly reduced under the considered climate scenarios when all the strategies are implemented. Overall, the total annual primary energy for operating the building versions decreased by 49–54 % This study emphasises the importance of considering different design strategies and measures in minimising the operation energy use and the potential risks of overheating in low-energy residential buildings under future climate scenarios.

Introduction

The accumulation of greenhouse gases (GHGs) in the atmosphere has increased to significant levels since the pre-industrial era (IPCC Intergovermental Panel on Climate Change, 2013). Global GHG emissions nearly doubled in 2010 compared to 1970 levels (IPCC Intergovernmental Panel on Climate Change, 2014c). Similarly, GHG emissions from the building sector more than double over the same period and this accounted for 19 % of all global GHG emissions (IEA 2012). Energy-related CO_2 emissions represent the largest share of global GHG emissions, accounting for about 60 % of global emissions (IEA International Energy Agency, 2015). GHGs emissions are mainly due to human activities and affect the earth's balance of radiative energy, increasing the mean surface temperature and causing a wide range of negative impacts. Average temperature over the European (EU) land area for the decade 2002–2011 is 1.3 °C higher than that for 1850–1899 (IPCC Intergovernmental Panel on Climate Change, 2014a). In Sweden, predictions for 2100, based on different climate scenarios show annual average temperature rise of 2–6 °C compared to the average for 1961–1990 with the biggest changes occurring in winter (SMHI Swedish Meteorological and Hydrological Institute, 2015). Climate change may influence buildings' energy use and therefore design strategies must include effective mitigation and adaptation measures to address the negative impacts of climate change.

The construction and operation of buildings are energy intensive, presenting many climatic and environmental challenges. Residential and service buildings account for about 38 % of the total final energy use in Europe (Eurostat, 2016) and in Sweden (Swedish Energy Agency, 2016). A large part of the final operation energy use of the residential building stock in many EU countries is attributable to space heating (Saheb, Bódis, Szabó, Ossenbrink, & Panev, 2015). However, under climate change these patterns of energy use may be influenced, affecting buildings' indoor environment and comfort levels, especially in highly energy efficient buildings. Several performance evaluations of low-energy buildings under different climates contexts suggest high cooling demands and overheating risks (Badescu, Laaser, & Crutescu, 2010; Mlakar & Štrancar, 2011; Rohdin, Molin, & Moshfegh, 2014; Tabatabaei Sameni, Gaterell, Montazami, & Ahmed, 2015).

Several studies have explored the impact of climate change on the heating and cooling demands of buildings in different climate contexts and show trends of decreasing heating and increasing cooling demands under climate change (Berger et al., 2014; Dodoo & Gustavsson, 2016; Wang & Chen, 2014). Few studies have analysed the implications of different building design strategies in the context of climate change. (Holmes & Hacker, 2007) analysed different ventilation design strategies for different building types in the United Kingdom (UK) considering climate change. They found that high thermal mass and a mixed-mode ventilation strategy give reduced energy use and comfortable indoor climate. (Gaterell & McEvoy, 2005) analysed different energy efficiency measures for a typical old residential building in the UK under climate change. The considered measures were roof insulation, heavy curtain or insulated shutters, double glazing and cavity wall insulation. Their results showed that double glazing gave the highest space heating savings and the lowest space cooling demand, compared to the initial single glazed windows. (Karimpour, Belusko, Xing, Boland, & Bruno, 2015) explored climate change effects on different design options to achieve energy efficient envelope for buildings in Australia. They considered different window glazing, floor covering, wall and roof insulation thicknesses, reflective roofs and foil under current and future climates. They observed that cooling demand becomes more important in highly insulated buildings. However, the effect of different building orientations and window sizes were not considered. Most of the reported studies that have analysed the impact of climate change on building thermal performance are based on the Special Report on Emissions Scenarios, with only a few studies (e.g. (Dodoo & Gustavsson, 2016)) based on the recently published Representative Concentration Pathways (RCPs) scenarios by (IPCC Intergovernmental Panel on Climate Change, 2014b).

New buildings present many possibilities to adopt design strategies to fit local climate conditions in order to optimise both heating and cooling demands with regards to climate change. In this study, we explore the influence of climate change on the annual energy use of a version of a multi-storey residential building in Sweden, considering different design strategies with the aim to minimise the space heating and cooling demands. The studied building version is modelled to meet the requirements of the Swedish passive house criteria (FEBY 12, 2012). The considered strategies include energy-efficient appliances and building technical installations, solar shading of windows, bypassing the ventilation heat recovery unit to control cooling, different combinations of window thermal transmittance (u-values) and solar transmittance (g-values), different façade orientation and share of window areas as well as mechanical cooling. The analysis is based on dynamic hour-by-hour energy balance calculations of the building version with and without the considered design strategies and under different climate scenarios to explore the impact of climate change on the thermal performance. Further, a system analysis approach is employed to assess the effect of the implemented design strategies on the primary energy use of the building version, taking into account the complete energy supply chain. Unlike simplified set of primary energy factors, this approach involves detailed analysis of the various activities and processes along the energy chains of the different energy supply systems, beginning from extraction, refining and conversion of natural resources, transport, conversion to heat and electricity, and distribution for final use.

BUILDING DESCRIPTION

This study is based on a recently completed multi-storey residential building in Växjö, Southern Sweden. The building is 6-storey high in prefab concrete frame and comprises 24 apartment units of 1–3 bedrooms with a total heated floor area of 1686 m^2. The foundation consists of 100 mm concrete slab on 300 and 200 mm layers of cellplast insulation and crushed stone, respectively. The external walls consist of 100 mm cellplast insulation sandwiched between 100 mm and 230 mm concrete panels on the outside and inside respectively. The intermediate floors are 250 mm concrete slabs and the ceiling floor consists of 250 mm concrete slab and 500 mm mineral wool insulation with wooden trusses and a roof covering over layers of asphalt-impregnated felt and plywood. The windows and external doors have clear glass double-glazed panels with wood frames, which are clad with aluminium profiles on the outside. The window and door u-value and g-value of the studied building are 1.2 W/m^2K and 0.6, respectively. The west façade has the largest window area of about 161.2 m^2, followed by the east façade with a total window area of 74.5 m^2. The north and south façades have the same share of window areas of 39.3 m^2 each. The building has balanced ventilation with a heat recovery system. Changes are modelled to the envelope characteristics of the building to meet the standard of the Swedish passive house criteria (FEBY 12, 2012). Figure 1 shows a photograph and typical floor plan of the building. The thermal properties of the passive house version are given in Table 1.

Method

The analysis is based on dynamic hour by hour energy balance simulation of the building version for recent and projected future climate conditions, including modelling different design strategies and using a systems analysis approach to explore climate change implications on the final and primary energy use.

REFERENCE AND FUTURE CLIMATE SCENARIOS

The energy performance of the building version was modelled for 1996–2005 as the reference period for the analysis and under 2050–2059 and 2090–2099, depicting mid-century (2050s) and end of century (2090s) future climate periods, respectively. The period 1996–2005 is suggested to be more representative of current climate conditions compared to 1961–1990 due to climate change (Remund, 2010; SMHI (Swedish Meteorological and Hydrological Institute), 2013). Future climate data based on global climate model (GCM) of the HadGEM2 Earth system for the county of Kronoberg, where the city of Växjö is situated were obtained from the regional climate model (RCA4) administered

Figure 1. Photograph (a) and typical floor plan (b) of the studied building.

Table 1. Thermal properties of the building version to the Swedish passive house criteria.

Building version	U-value (W/m²K)					Air leakage at 50 Pa (l/s m²)	Mechanical ventilation
	Ground floor	External walls	Windows	Doors	Roof		
Passivhus 2012	0.11	0.11	0.80	0.80	0.05	0.3	Balanced with (76 %) heat recovery

by the Rossby Centre of the Swedish Meteorological and Hydrological Institute (SMHI Swedish Meteorological and Hydrological Institute, 2011). The climate data from the RCA4 model are based on monthly resolutions and to obtain hourly resolution datasets for the future climate periods, they were downscaled using the morphing approach (Belcher, Hacker, & Powell, 2005) with 1961–1990 as the baseline period. The morphing approach is suggested to be reliable for producing future climate datasets consistent with current best projections for the purpose of thermal simulation for real building design (Belcher et al., 2005) and has been applied in several studies (Dodoo & Gustavsson, 2016; Rubio-Bellido, Pérez-Fargallo, & Pulido-Arcas, 2016) with similar trends in results. Variations in ambient temperature, solar radiation, wind speed and relative humidity are considered in the downscaled data for climate scenarios based on the Representative Concentration Pathways (RCPs) scenarios (IPCC Intergovernmental Panel on Climate Change, 2014b). The RCPs consist of one mitigation scenario leading to very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5) each characterized by atmospheric concentration of CO_2 equivalent of 450, 650, 850, and 1,370 ppm by 2100, respectively (IPCC Intergovermental Panel on Climate Change, 2013; IPCC Intergovernmental Panel on Climate Change, 2014b). The analyses in this study are based on RCPs 2.6, 4.5 and 8.5 climate scenarios. RCPs 4.5 and 8.5 characterise low and high radiative forcing levels, respectively and are suggested to reflect the contrast between currently feasible and business-as-usual climate change mitigation goals (Mora, 2013). RCP2.6 portrays ambitious climate change mitigation goals and is increasingly suggested to be unfeasible (Mora, 2013). However, the Conference of Parties (COP21) reached a consensus to limit global temperature rise below 2 °C, above pre-industrial levels by 2100 (UNFCCC United Nations Framework Convention on Climate Change, 2015). The 2 °C global temperature target is suggested to be achievable through a rapid transition to climate change mitigation goals similar to the RCP2.6 pathway (Sanford, Frumhoff, Luers, & Gulledge, 2014).

FINAL ENERGY CALCULATIONS

The VIP+ simulation software (StruSoft, 2012) was used to perform dynamic hour-by-hour energy balance calculations of the building version under the different climate scenarios before and after implementing the considered design strategies. The final energy calculations include space heating and cooling, tap water heating and electricity for ventilation and household equipment and lighting. The annual hourly indoor air temperature profiles were also modelled with the VIP+ software and the percentage of annual operating hours that the cooling set point and overheating temperature threshold of 28 °C based on (CIBSE, 2006) are exceeded, were calculated. The VIP+ simulation software performs detailed multi-zone and multi-dimensional modelling of thermal bridges and heat storage capacity of building envelope components, taking into account the interactions between building design, geometry, thermal characteristics of building envelope elements and climate conditions as well as HVAC and other technical installation for different building occupancy and operational schedules. The software is validated by the International Energy Agency's BESTEST, ANSI/ ASHRAE Standard 140 and CEN 15265. The analysis was done with the climate data for the city of Växjö (latitude 56° 52´ N, longitude 14° 48´ E), where the building is located. Key input parameter values and assumptions for the energy balance calculations are presented in Table 2.

DESIGN STRATEGIES

The planning and construction of new buildings present a wide range of possibilities to optimise their designs to the building's local climate and use different technologies to minimise energy

Table 2. Key input parameters and assumptions for energy balance modelling of initial building (before implemented strategies).

Description	Parameter	Values/ assumptions	Comments
Indoor temperature set points	Heating	21 ºC/18 ºC	Living area/ common area
	Cooling	27 ºC	Estimated
Heat gains	Persons	80 W/person	Average value based on (SVEBY, 2013) with variable annual profile considered in simulation
	Lighting and appliance	2.94 W/m2	Standard equipment. Average values estimated based on data from (Aníbal de Almeida et al., 2008) with annual variations considered in simulation
	Hot water circulation	1.05 W/m^2 (average)	Standard equipment. Average values estimated based on (Isover, 2016) with annual variations considered in simulation
Hot water	Annual average intensity	2.85 W/m^2	Standard taps and shower heads. Average value based on (SVEBY, 2013) with annual variations considered in simulation
Electric power use	Annual average intensity	3.41 W/m^2	Standard electric equipment and lighting. Estimated based on data from (Aníbal de Almeida et al., 2008)
Ventilation, pumps, heat exchanger and fans	Air change rate [a]	0.1/0.35 l/sm^2	Based on (BBR Boverkets Byggregler, 2015)
	Heat recovery	76 %	Based on (Swedish Energy Agency, 2010)
	Fan pressure	400 Pa	Estimated based on (StruSoft, 2012)
	Fan efficiency	33 %	Based on (Brelih, 2012)

[a] *Air change rate of 0.1 and 0.35 l/sm^2 are considered when the building is assumed to be unoccupied and occupied, respectively, based on Swedish building code.*

use. The thermal performance of the building version before and after the implemented design strategies are analysed and compared under the different climate scenarios. The considered strategies are implemented cumulatively in the following order based on simplified assumptions and ease of implementation:

- Efficient household equipment and technical installations based on best available technology (BAT)

The household equipment and technical installations in the initial building version are assumed to be of today's standard technology. These are changed to efficient household equipment and technical installations based on best available technology (BAT) to analyse the effect on energy use under changing climates. Values for the key input parameters and assumptions for household equipment and technical installations based on BAT are given in Table 3. The heat gains from electrical appliances, lighting and persons are modelled, taking into account seasonal and daily variations based on average profiles for Swedish buildings (Liu, Rohdin, & Moshfegh, 2015; Lundström & Wallin, 2016).

- By-passing the ventilation heat recovery (VHR) unit when the cooling set point is exceeded.
- Solar shading of windows to be activated when the cooling set point is exceeded.
- Different combinations of window thermal (u-values) and solar (g-values) transmittances.
- Decreasing or increasing the proportion of window areas on different façades by 20 and 40 %.
- Different façades orientations to optimise space heating and cooling demand.
- Mechanical cooling with air conditioners when cooling set point is exceeded.

PRIMARY ENERGY CALCULATIONS

The ENSYST program was used to calculate the primary energy use, required to provide the final energy for space and tap water heating and electricity for space cooling, ventilation as well as for household equipment and lighting for the building version before and after the implemented strategies and measures. ENSYST calculates primary energy use, taking into account the complete energy chains of the different energy supply systems from natural resources extracted, transported and refined to produce the supplied final energy to the building version. Typically, multi-storey apartment buildings are heated with district heating in Sweden (Swedish Energy Agency, 2015b). The building is assumed to be heated with a biomass-based district heating system, comprising a combined heat and power (CHP) plant using wood chips and heat only boilers (HOB) using wood chips or wood powder producing 68, 30.5, and 1.5 %, respectively, of the total district heat production. A CHP plant cogenerates heat and electricity and therefore allocation issues may arise. The cogenerated electricity from the CHP plant is assumed to replace electricity from a stand-alone plant with similar fuel and technology as the CHP plant based on the substitution method to avoid co-products allocation (Gustavsson & Karlsson, 2006). The primary energy use for the replaced electricity in the stand-alone plant is thus subtracted from that of the CHP plant to obtain the primary energy for the heat. The electricity for the air conditioners, ventilation and household equipment is assumed to be covered by a stand-alone biomass-

Table 3. Key input parameters and assumptions for household equipment and technical installations based on best available technology (BAT).

Description	Parameter	Values/ assumptions	Comments
Heat gains	Lighting and appliance	1.35 W/m^2	Efficient equipment. Average values with annual variations considered in simulation. Estimated based on data from (Aníbal de Almeida et al., 2008).
	Hot water circulation	0.68 W/m^2 (average)	Efficient equipment. Average values with annual variations considered in simulation. Estimated based on data from (Isover, 2016).
	Sun		Based on climate file.
Hot water	Annual average intensity	1.75 W/m^2	Efficient taps and shower heads based on (Swedish Energy Agency, 2015a).
Electric power use	Annual average intensity	1.69 W/m^2	Efficient electric equipment and lighting. Estimated based on data from (Aníbal de Almeida et al., 2008).
Ventilation, pumps, heat exchanger and fans	Heat recovery	80 %	Based on (Rohdin et al., 2014; Smeds & Wall, 2007; Swedish Energy Agency, 2010)
	Fan pressure	200 Pa	Estimated
	Fan efficiency	50 %	Based on (Camfil, 2014).

based steam turbine (BST) marginal plant. The efficiencies and capacities of the considered energy supply systems are given in Table 4, which shows parameter values used in the ENSYST program for the calculation of the primary energy use linked to final heat and electricity use of the analysed building version.

Table 4. Efficiencies and capacities of considered energy supply technologies based on (Truong, Dodoo, & Gustavsson, 2014).

Energy supply technology	Capacity	Efficiency
Stand-alone power plant:	(MW_{elec})	(η_{elec})
Biomass steam turbine (BST)	400	0.40
Cogeneration plants:	(MW_{heat})	(η_{elec}/η_{heat})
CHP-BST	81	0.29/0.78
Heat-only boilers:	(MW_{heat})	(η_{heat})
Wood powder	50	0.88
Wood chip	50	1.08
End-use heating and cooling:		(η)
District heating heat exchanger		0.95
Room air conditioners		3

Results

Table 5 shows the annual final energy demand for space heating and cooling, tap water heating and electricity for ventilation and household equipment of the initial (before implemented design strategies) building version for the reference climate period of 1996–2005. Electricity for household equipment and ventilation together form the largest share (43 %) of the operation energy demand, followed by tap water heating (24 %). The share of space heating and space cooling is similar, representing 16 and 17 %, respectively. Space heating and electricity for household equipment give the lowest and highest primary energy use, respectively.

Figure 2 illustrates the changes in the space heating and cooling demands of the initial building version under the reference and future climate scenarios. Space heating demand decreases, while space cooling demand increases for the initial building version under the future climate scenarios, compared to the reference. Space heating decreased by 14–31 % while space cooling increased by 1–18 % for mid-century (2050s) climate scenarios. For end of century (2090s) scenarios, space heating decreased by 14–53 % while space cooling increased by 30–59 % except for RCP2.6, where cooling decreased by 1 %. The variations in space heating demands for mid-century and end of century for RCPs 2.6 and 4.5 are small compared to that for RCP8.5. Similarly, the variation in cooling demands between mid-century and end of century periods for RCP2.6 is small, but more significant for RCP4.5 and for RCP8.5 climate scenarios. The space cooling demand for the initial building version becomes more significant than space heating under all the considered climate scenarios.

The modelled annual hourly indoor air temperature profiles of the initial building version are shown in Figure 3 for mid-century and end of century periods. The profiles follow similar trends for both climate periods but are specifically higher under RCP8.5 for the end of century period. Indoor air temperatures exceeded the cooling set point by 43 % of the total annual operating hours under the reference climate. The corresponding numbers are 45–48 % and 45–53 % of the total annual operating hours for mid-century and end of century periods, respectively. Assuming an overheating temperature threshold of 28 °C for not more than 1 % of annual occupied time based on recommendations by (CIBSE, 2006), overheating occurs under all the considered climates for the initial building version. The proportion of hours that indoor air temperatures exceeded the overheating threshold was 40 % of the total annual operating hours of the initial building version under the reference climate and between 41–44 % and 41–51 % under mid-century and end of century climate scenarios, respectively.

The variations in space heating and cooling demands of the improved building version when the different design strategies are implemented cumulatively are shown in Figure 4. The combination of u- and g-values as well as the orientation and share of window areas are based on those resulting in the lowest total space heating and cooling demand for the building version under the different climate scenarios. Window u-value of 0.6 W/m²/K and g-value of 0.2, north orientation of the largest window areas as well as reduced window areas by 40 % consistently gave the lowest final space heating and cooling demands for the building version under the different climate scenarios. Space heating demand for the building version increased averagely by about 6 kWh/m², representing 59 % under the considered climate scenarios, when all the strategies are implemented cumulatively. On the other hand, space cooling demand decreased by 17 kWh/m², representing 98 %. Overall, the total annual final energy demand of the improved building version decreased by 40 % under the reference climate when all the strategies are implemented. The corresponding decreases are between 43–46 % and 42–51 % for mid-century and end of century climates, respectively.

The modelled annual hourly indoor temperature profiles of the improved building version after the implemented strategies in Figure 5 show that the proportion of hours when the cooling set point is exceeded, reduced significantly from 47 to 4 % of the total annual operating time under RCP 4.5 and from 53 to 17 % under RCP 8.5 both for end of century period. Overheating is avoided for the improved building version under all climate scenarios, except under RCP8.5-2090s for which the proportion of hours that the overheating threshold is exceeded reduced significantly from 51 to 6 %. The proportion of hours that the overheating threshold is exceeded under the rest of the climate scenarios ranged between 0-0.1 % of the total annual operating hours, well below the 1 % limit.

Table 6 gives the total operation primary energy use for the initial building version and for the improved version after the different design strategies are implemented cumulatively under different climate scenarios. The primary energy use includes space heating and cooling, tap water heating and electricity for household equipment and ventilation. Air conditioners are assumed to meet the remaining cooling demand after implementing each successive design strategy. Total primary energy use for operation of the improved building version decreased by 49% under the reference climate of 1996–2005 when the different design strategies are implemented. The corresponding reductions for the future climate scenarios are between 50–51 % and 50–54 % for mid-century and end of century periods, respectively. Household equipment and technical installations based on BAT give the biggest decrease in primary energy use, while the effectiveness of the other design strategies in reducing primary energy use varies with the climate scenarios.

Table 5. Annual final energy demand and primary energy use for the initial Passivhus 2012 building version under the reference climate (1996–2005).

Description	Annual final energy demand (kWh/m²)	Annual primary energy use (kWh/m²)
Space heating	13.6	8.7
Space cooling	14.9	13.6
Tap water heating	21	13.4
Ventilation electricity	5.2	14.2
Household electricity	31.6	86.1
Total	86.4	136.1

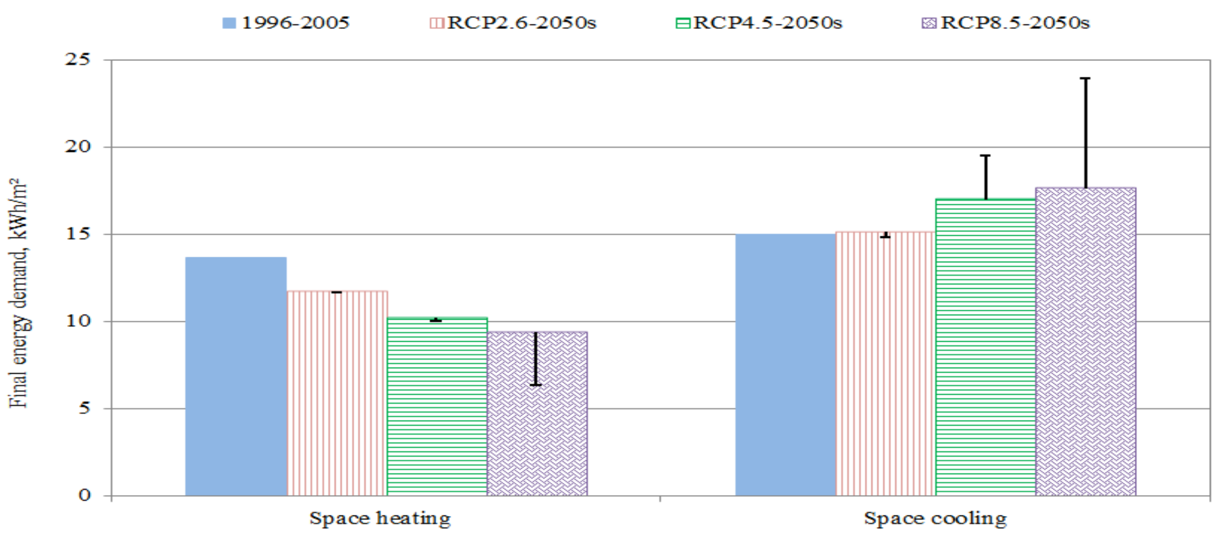

Figure 2. Space heating and cooling demands of the initial (before implemented design strategies) building version under different climate scenarios. The main bars show mid-century (2050s), while the error bars show end of century (2090s) scenarios.

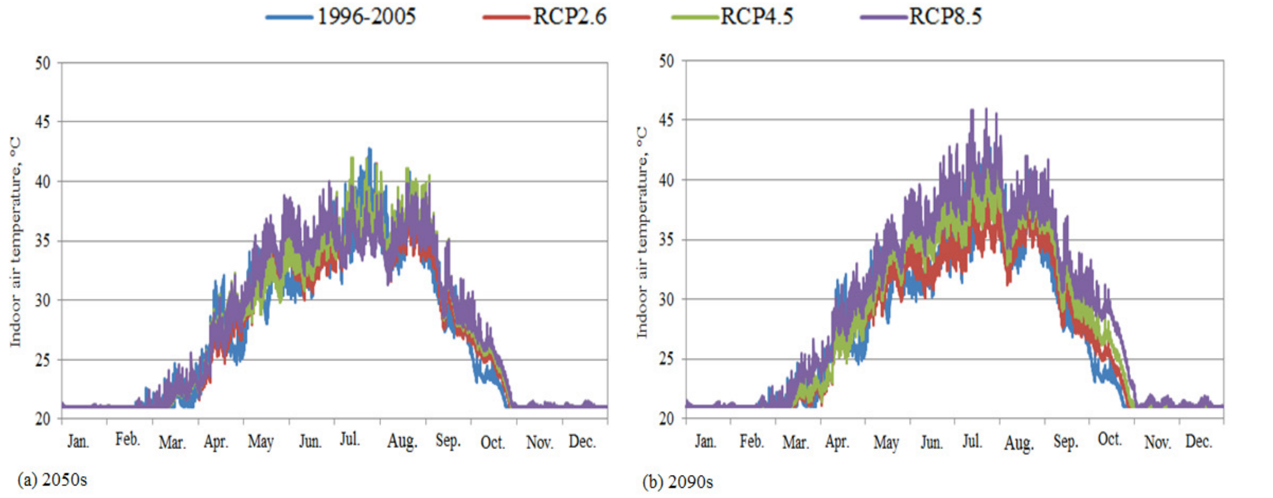

Figure 3. Annual hourly indoor air temperature profile for the initial (before implemented design strategies) building version under different climate scenarios.

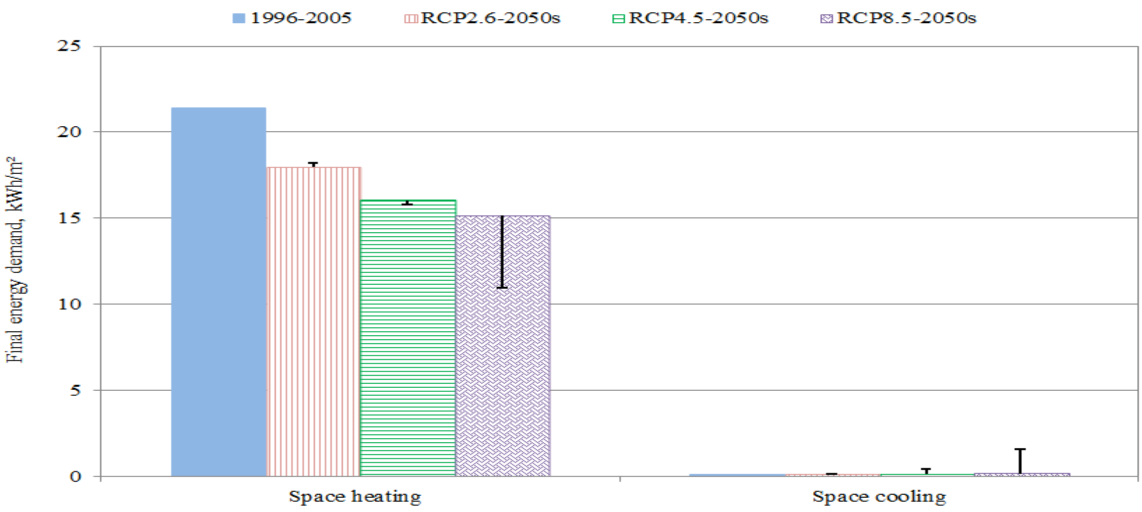

Figure 4. Space heating and cooling demands of the improved (after implemented design strategies) building version under different climate scenarios. The main bars show mid-century (2050s), while the error bars show end of century (2090s) scenarios.

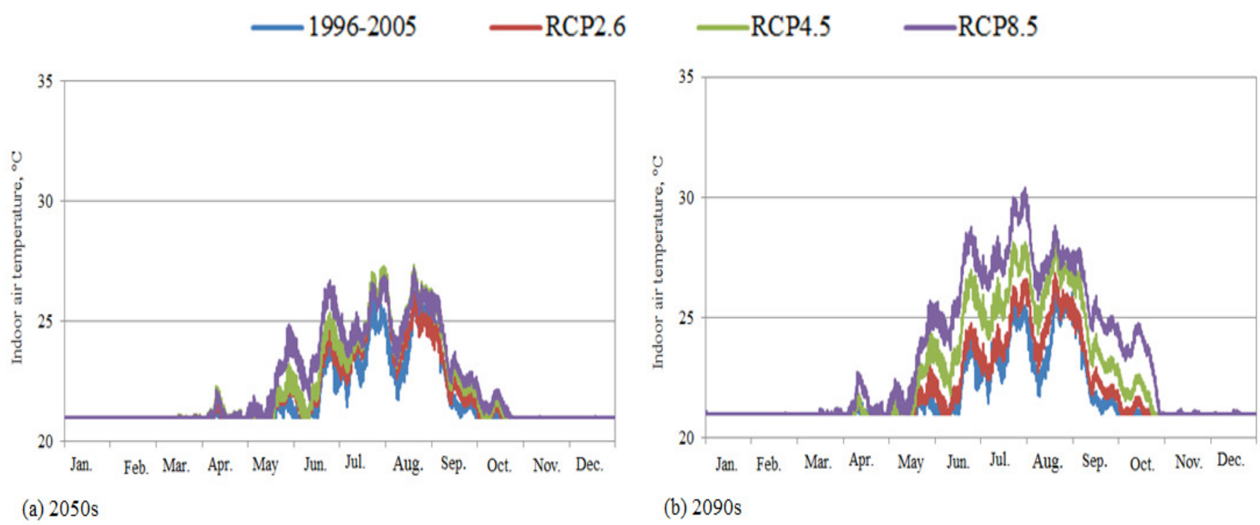

Figure 5. Annual hourly indoor air temperature profile for the improved (after implemented design strategies) building version under different climate scenarios.

Table 6. Total annual primary energy use (kWh/m²) for operating the building version before and after implementing different design strategies cumulatively under different climate scenarios.

Description	1996–2005	RCP2.6	RCP4.5	RCP8.5
2050s				
Initial with standard technology	136.1	135.0	135.7	135.7
+ BAT	79.0	77.4	77.8	77.6
+ By-pass of VHR unit	76.2	74.9	75.3	75.3
+ Shading	72.2	70.5	70.2	69.7
+ U and g-values	71.2	69.1	67.9	67.3
+ Orientation	71.3	69.1	67.8	67.2
+ Window areas	69.9	67.7	66.5	66.0
2090s				
Initial with standard technology	136.1	134.7	137.9	139.5
+ BAT	79.0	77.2	79.8	79.9
+ By-pass of VHR unit	76.2	74.8	77.6	78.1
+ Shading	72.2	70.5	71.3	70.8
+ U and g-values	71.2	69.2	68.3	66.3
+ Orientation	71.3	69.2	68.1	65.9
+ Window areas	69.9	67.9	66.6	64.6

Discussion and conclusions

The effects of climate change on the space heating and cooling demands of a residential building version designed to the Swedish passive house criteria have been explored in this study. Our analysis shows significant changes in the space heating and cooling demands of the initial building version under future climate scenarios, compared to the reference. Space heating demand generally decreased while space cooling demand increased considerably under future climate scenarios. The increases in space cooling demands are more significant for end of century than mid-century periods, except for the RCP2.6 climate scenario. For RCP2.6, space cooling is slightly lower for RCP2.6-2090s compared to RCP2.6-2050s, reflecting underlying assumptions of a peak and decline pathway of radiative forcing based on stringent mitigation goals to achieve substantial GHG emissions reductions (van Vuuren et al., 2011). RCP2.6 scenario is reported as the closest to 2 °C global temperature target and in line with ambitions of the Paris agreement (UNFCCC United Nations Framework Convention on Climate Change, 2015). Space cooling demand is more significant than space heating demand for the initial building version under all the considered climate scenarios with high risks of overheating. This trend is similar to those observed in the performance assessment and analyses of several low energy buildings in different climate contexts (Dodoo & Gustavsson, 2016; Rohdin et al., 2014; Tabatabaei Sameni et al., 2015). As the number of low energy buildings is expected to increase across the EU in line with stringent regulations, strategies to minimise both space heating and cooling demands need to be incorporated in the design of such buildings in the context of climate change. The space cooling demands were significantly reduced for the improved building version with all design strategies implemented under the climate change scenarios and overheating was avoided except under RCP8.5 for end of century period. Among the considered strategies, household equipment and technical installations based on BAT gave the biggest decrease in total primary energy use for the improved building version under the considered climate scenarios and energy supply systems. This is followed by shading while the effectiveness of the other strategies varied depending on the climate scenario. The impact of varying the shares of window areas and orientations was found to be minor if all the other design strategies are implemented before. Considering a 50 year life time for windows, the choice of windows may be based on optimised u- and g-values, considering climate change for the next coming 50 years. Also, the technical development of more energy efficient household equipment and technical installations will help to reduce future cooling demands if BAT is chosen when these types of equipment and installations have to be renewed. Overall, with the implemented strategies the total annual primary energy use for operation was reduced between 49–54 % under the different climate change scenarios.

Based on costs, design specifications and practical application of the considered strategies, the choice of strategy or order of implementing them may vary. Different buildings may require different sets of strategies in achieving lower energy demands under future climate scenarios. These factors may be explored in more detail in further studies.

The variations in the share of window areas and window properties may affect the quantities of materials required for the building frame, and hence the production primary energy use. The importance of the choice of frame materials on building production energy use, especially for low energy buildings, has been emphasised in different studies (Cabeza et al., 2013; Takano et al., 2015). This has not been considered here and further studies may explore the implications of the analysed designed strategies for low energy building systems with different frame materials under future climate scenarios in a life cycle perspective.

Daylighting benefits may be significant in climates with high solar radiation and daylight availability. However, daylight benefits are limited in the cold season in Nordic countries such as Sweden due to high latitudes and low availability (Dubois & Blomsterberg, 2011). The considered variations in the share of window areas meet the code requirement for minimum daylight accessibility recommended by the Swedish building code. Nevertheless, the potential benefits of daylight in combination with other measures such as electric lighting systems and inner wall reflectance for residential buildings under climate change may be explored in further studies.

Uncertainties linked to climate data and future climate projections may affect the results of our analysis. Future climate projections are based on advanced and high resolution Global Climate models (GCMs), which continue to improve over time. GCMs are reported as the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations (IPCC Intergovernmental Panel on Climate Change, 2013). The analyses in this study are based the most recent climate scenarios developed by IPCC. The efficiency of energy supply systems and COP of air conditioners as considered here may change over time and this may influence the effectiveness of the considered strategies and measures.

Overall, this study shows the importance of considering different measures as BAT and effective design strategies as shading in minimising the operation energy use and the potential risks of overheating in low-energy residential buildings under climate change.

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