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Energy and indoor thermal comfort performance of a Swedish residential building under future climate change conditions

Ambrose Dodoo[1,*]

[1]Department of Building Technology, Linnaeus University, Växjö, Sweden

Abstract. The latest climate change projections for Sweden suggest mean annual temperature increase of up to 5.5 °C by 2100, compared to 1961-1990 levels. In this study we investigate the potential impacts of climate change on the energy demand for space conditioning, overheating risk and indoor thermal comfort of a modern multi-storey residential building in Sweden. We explore climate change adaptation strategies to improve the building's performance under the climate change conditions, including increased ventilation, solar shading, improved windows and mechanical cooling. The building is analysed under future climate projections for the 2050-2059 time frame, with representative concentration pathway (RCP) 2.6, 4.5 and 8.5 scenarios. The building's performances under these future climates are compared to those under the historical climate of 1961-1990 and recent climate of 1981-2010. The results suggest that climate change will significantly influence energy performance and indoor comfort conditions of buildings in the Swedish context. Overheating hours and Predicted Percentage of Dissatisfied (PPD) increased significantly under the future climate scenarios. Furthermore space heating demand is reduced and cooling demand is increased for the studied building. However, effective adaptation strategies significantly improved the buildings' energy and indoor climate performances under both current and future climate conditions.

1 Introduction

The latest assessment report of the Intergovernmental Panel on Climate Change reiterated that increasing levels of anthropogenic greenhouse gases (GHGs) in the atmosphere is destabilizing the earth's climate system [1]. Anthropogenic activities are estimated to have caused between 0.8°C to 1.2°C warming of the earth's climate since the pre-industrial period [2]. Furthermore, global land surface average temperatures for the period 2015-2019 are reported to be the highest on modern record, with 2019 being the second warmest year, after 2016 [3, 4]. Climate observations in Sweden show that a warming of about 1.0°C has already occurred since 1960 [5]. With the current rate of increase, the global warming is projected to reach 1.5°C between 2030 and 2052, unless timely and appropriate actions are taken to reduce GHGs emissions [2].

Fossil fuels account for a vast share of the primary energy use in our society today [6, 7], and contribute considerably to climate change [1, 8]. The International Energy Agency anticipates that global CO_2 emission may increase by 20% by 2035 with the current trends in energy use and planned measures to mitigate climate change [9]. This might result in global average temperature rise of about 3.6°C relative to pre-industrial levels, much more than suggested in the Paris climate agreement [10, 11]. The Paris climate agreement suggests keeping temperature rise below 2°C and aiming for a temperature rise of 1.5°C [11].

Buildings are responsible for about 36% of CO_2 emissions in the European Union (EU) [12], contributing substantially to climate change. In consequence, climate change will impact on buildings' energy and indoor climate performance [13, 14]. Mitigation and adaptation strategies may be implemented to minimise potential risks that may be associated with climate change. Climate change mitigation strategies seek to minimise emissions of atmospheric GHGs, while climate change adaptation strategies may aim to ensure tolerable and resilient performance of the built environment. Adaptation measures for buildings may aim at ensuring comfortable indoor climate and could encompass passive and active measures to reduce cooling load and overheating risk which are expected to be dominant under climate change conditions [15, 16].

Studies to increase understanding of how climate change may affect thermal performance of buildings are essential to inform appropriate climate mitigation and adaptation strategies. Generally, studies in different countries reported significant changes in building space conditioning energy use, with the dominance of cooling increasing and heating decreasing, under future climate change scenarios [16-22]. However, the overall effect of the projected future climate change varies significantly for different locations and buildings.

Few studies in Sweden have been reported on the implications of climate change for energy and indoor climate performance of buildings, with most of these based on the Special Report on Emissions Scenarios

* Corresponding author: ambrose.dodoo@lnu.se

(SRES) or simplified future weather data, e.g. [15, 19, 23, 24]. Fewer Swedish studies, e.g. [25, 26] are based on the representative concentration pathway (RCP) climate scenarios which are the latest set of future climate projections [1]. Still, these studies mostly focused on the potential impacts on space heating and cooling. Swedish studies which also analyse the impact of climate change on indoor thermal comfort are lacking. Thorsson et al. [27] investigated the implications of climate change for outdoor thermal comfort conditions in the Swedish city of Gothenburg, focusing on the influence of urban geometry.

In this study we investigate the potential changes in space conditioning energy demand and thermal comfort of a Swedish case-study building due to future climate change. We explore climate change adaptation strategies to improve the building's thermal performance under the climate change conditions.

2 Methods

Energy balance and indoor climate modelling are used in this study to explore the implications of future changes in climate for a case-study apartment building.

2.1. Case-study building

The building for this analysis is a six-storey reinforced concrete structure with 24 apartments, built in 2014 in Växjö (lat. 56°87′37″ N; long. 14°48′33″ E), Sweden. It is heated with district heat and has mechanical ventilation with heat recovery (VHR) system. No mechanical cooling system is installed in the building, as with typical Swedish residential buildings, due to the low cooling loads presently. Fig. 1 presents the building's photograph and layout, and Table 1 gives its key thermal characteristics.

Fig. 1. Photograph and ground floor plan of the building.

Table 1. Construction and thermal properties of the building.

Description	Values
Living / common area (m^2)	1420/ 266
Elements U-values (W/m^2K):	
Ground floor	0.11
Exterior walls	0.32
Windows	1.2
Doors	1.2
Roof	0.08
Infiltration (l/s m^2 @50 Pa)	0.6

2.2 Climate datasets and future scenarios

2.2.1 Historical and recent climates

As baselines, the thermal performance of the building is modelled with the long-term historical climate dataset for 1961-1990, which denotes the climate normal period in Sweden [28], and with the climate dataset for the period 1981-2010 which is considered to represent the recent climate.

2.2.2 Future climate scenarios

RCP2.6, RCP4.5 and RCP8.5 climate change scenarios for the 2050–2059 (2050s) time frame are considered in this study. These scenarios respectively represent low, medium and high climate change projections for the time frame considered. Regionally downscaled HadGEM2-ES data for these scenarios from the RCA4 model [29] are used in this analysis. Fig. 2 shows projected temperature changes for the scenarios for Växjö's county of Kronoberg. The temperature changes are relative to the average for 1960-1990.

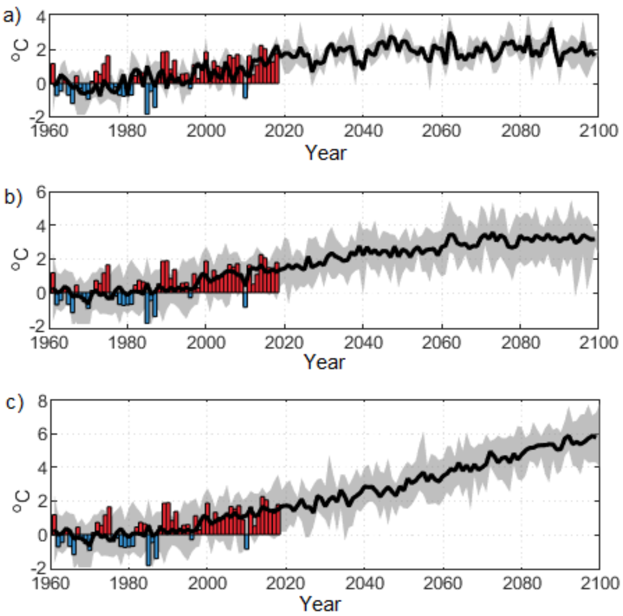

Fig. 2. Temperature changes relative to 1960-1990 average for Växjö's county of Kronoberg, for RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5(c), (Adapted from [5]).

Table 2 presents a summary of the average, maximum and minimum outdoor air temperatures for the climate datasets and scenarios.

Table 2. Outdoor air temperatures for climate datasets and scenarios.

Description	Outdoor air temperature (°C)		
	Average	Maximum	Minimum
Historical (1961-1990)	6.4	27.5	-16.0
Recent (1996-2005)	7.0	28.0	-17.0
RCP2.6-2050s	8.0	29.0	-14.0
RCP4.5-2050s	9.0	29.0	-14.0
RCP8.5-2050s	10.0	29.0	-13.0

Fig. 3 shows projected wind gust under the future scenarios for the studied location.

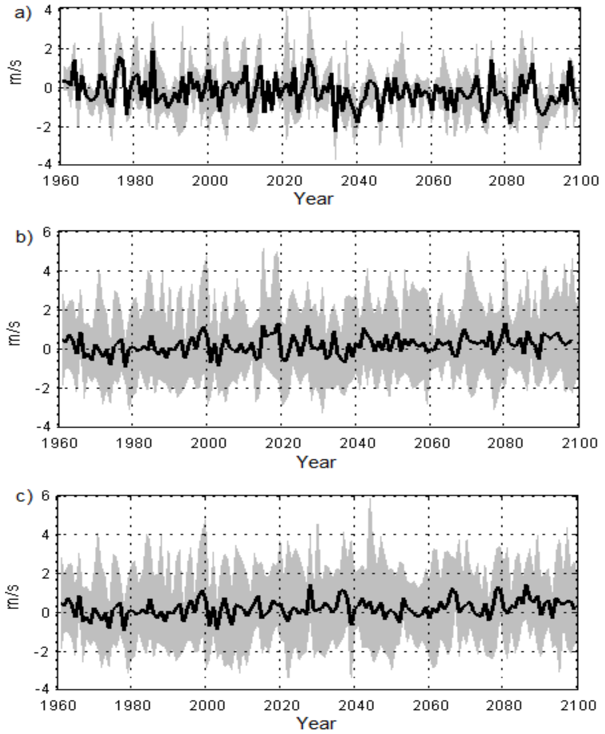

Fig. 3. Wind gust changes relative to 1960-1990 average for Växjö's county of Kronoberg, for RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5(c), (Adapted from [5]).

2.3 Climate datasets downscaling

The future climate scenarios datasets from the RCA4, encompassing outdoor air temperature, solar radiation, wind speed and relative humidity, are at monthly time-step and are downscaled to hourly time-step using an approach described by Belcher et al. [30]. The approach consist of shifting and stretching a baseline hourly climate data with adjustment algorithms that takes into account future monthly mean climate values projected for climate change conditions. The 1961-1990 climate dataset is used as baseline in the downscaling.

2.4 Simulations and analyses

2.4.1 Energy balance modelling

The VIP-Energy software [31] is used to model the energy and indoor thermal performances of the building under the historical, recent and projected future climates for Växjö. The software is a dynamic simulation program which models energy balance and indoor climate of buildings in hourly time-step. It is a whole building energy simulation program and it calculates the energy demand for heating, cooling, lighting and ventilating a building. Major input parameters taken into account when conducting simulations in VIP-Energy include thermal envelope properties, orientations, HVAC systems, heat gains from lighting, appliances and human bodies, and occupancy and building operation schedules, indoor air temperature and outdoor climate parameters including dry bulb temperature, wind velocity, relative humidity and direct normal radiation. Validations with International Energy Agency's BESTEST, ASHRAE 140-2007 and CEN 15265 showed that the software can give accurate predictions of buildings' thermal performances in comparison with other state-of-the art simulation programs. Key input data for the energy balance analysis are presented in Table 3.

Table 3. Key data for the energy balance modelling.

Parameter	Data	Remark/Source
Heating set-point	22/ 18ºC	Living / common areas, [32]
Cooling set-point	26ºC	Dodoo et al. [32]
Heat gains:		
Persons	1.00 W/m^2	Dodoo et al. [32]
Electrical process	2.74 W/m^2	Standard appliances, [33]
Sun	Calculated	VIP-Energy simulation [31]
Ventilation:		
Air change rate	0.35 l /s m^2	Building code [34]
Fan efficiency	50%	Camfil [35]
VHR efficiency	75%	Dodoo et al. [32]
Building occupancy	15 hrs/day	5.00 pm–8.00 am, [33]

2.4.2 Thermal comfort modelling

Hourly indoor air and operative temperatures as well as Predicted Percentage Dissatisfied (PPD) index during summer are modelled for the living area of the building for the different climates, using the VIP-Energy software [31]. The PPD index is calculated according to ISO7730 [36], based on the climate file data and VIP-Energy's default assumption on person's clothing and metabolism.

The risk of overheating is analysed for the living area of the building under the different climates considering different guidelines – (i) the Swedish National Board of Health and Welfare recommendation which suggests that indoor air temperatures in residential buildings should not exceed 26°C during summer [37], and (ii) the Chartered Institution of Building Services Engineers guideline which suggests that a building is overheated if indoor temperature exceeds 28 °C in living areas or 26 °C in bedrooms for more than 1% of the occupied time within a year [38].

2.4.3 Adaptation strategies

Plausible measures are analysed to explore strategies to reduce cooling demands and overheating risks, and thereby improve the building's indoor thermal performance under climate change conditions. The analysed measures include increased ventilation rate and implementation of external window shading devices, besides mechanical cooling with air conditioners. The external shading devices are assumed to be fitted above the windows and activated if indoor air temperature exceeds 26°C. The minimum ventilation rate of 0.35 l/s m^2 required by the Swedish building code is assumed to be doubled when the indoor temperature exceeds 26°C. The building is modelled with and without the measures to evaluate their effectiveness under the different climates and scenarios.

3 Results

3.1 Energy performance

Fig. 4 shows the annual energy balance of the building under the different climates and demonstrates the contributions of different energy flows for the building. Heat supply, encompassing space and tap water heating, dominates for the supplied energy whiles transmissions dominates the emitted energy. Transmissions and ventilation heat losses, and hence heat supply decreased under the future climate scenarios. Space cooling accounts for a small share of the energy flow, and becomes increasingly noticeable under the future climates.

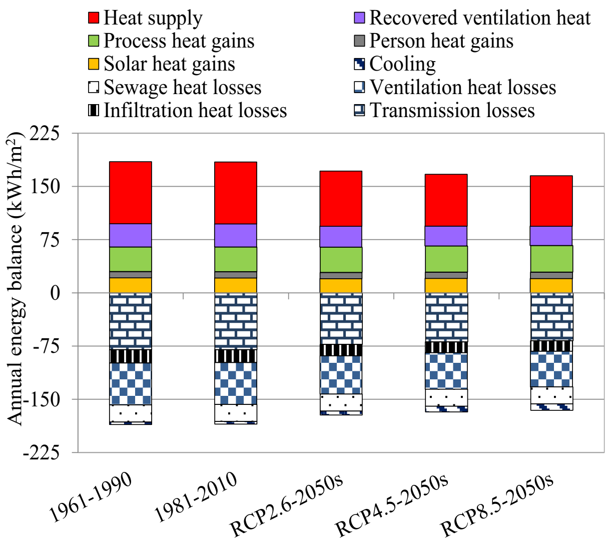

Fig. 4. Annual energy balance of the building under the different climates.

Fig. 5 shows the annual space heating and cooling demands of the building under the different climates. The energy demands for space heating decreased whilst space cooling increased under the future climates.

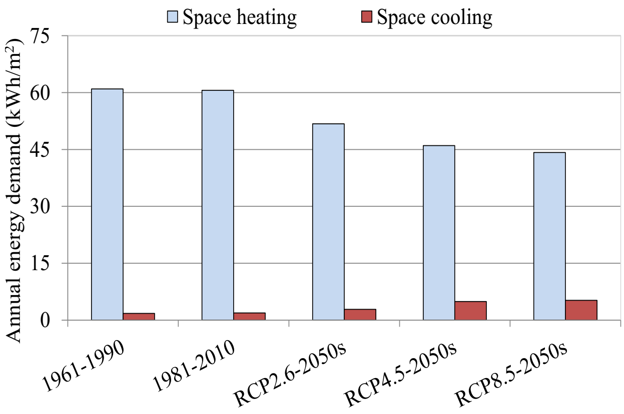

Fig. 5. Annual energy demands for space heating and cooling of the building under historical, recent and future climates.

As shown in Fig. 6, the space heating demand of the building decreased 1%, 15%, 25% and 27% under the recent (1981-2010), RCP2.6-2050s, RCP4.5-2050s and RCP8.5-2050s climates, respectively, relative to the historical (1961-1990) climate. Correspondingly, space cooling demand of the building increased by 5%, 60%, 175% and 192%, respectively.

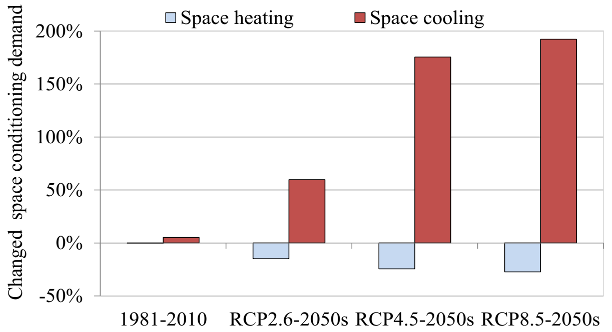

Fig. 6. Changed annual space heating and space cooling demands relative to the historical climate of 1961-1990.

3.2 Comfort performance

Fig. 7 gives the hourly indoor air temperature profiles of the living area of the building without cooling intervention under the historical (1961-1990) and recent (1981-2010) climates, while Fig. 8 gives that under the future climates of RCP2.6-2050s, RCP4.5-2050s and RCP8.5-2050s. These show that indoor air temperatures increased between June and August under the future climates compared to the historical and recent climates. Fig. 9 gives the outdoor air temperature as well as the operative temperature of the building without cooling intervention for the RCP4.5-2050s scenario.

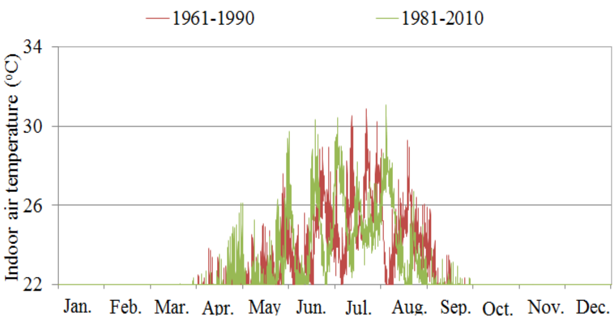

Fig. 7. Annual hourly indoor air temperatures for the building without cooling intervention for historical and recent climates.

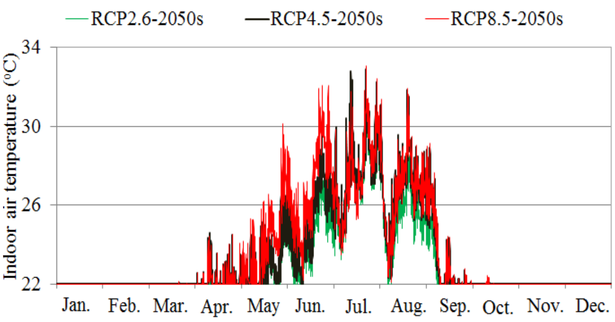

Fig. 8. Annual hourly indoor air temperatures for the building without cooling intervention under future climate scenarios.

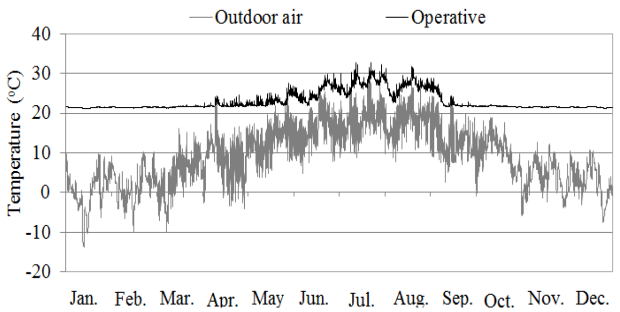

Fig. 9. Annual hourly outdoor air temperature and operative temperature for the building without cooling intervention for RCP4.5-2050s scenario.

Average hourly indoor air and operative temperatures as well as PPD values for the living area of the building during summer (1st June to 31st August) under the different climates are summarized in Table 4. The average indoor air temperatures are about 1.0, 1.8 and 2.4°C higher for the RCP2.6-2050s, RCP4.5-2050s and RCP8.5-2050s climates, respectively, compared to the recent climate of 1981-2010. The trend is similar for the operative temperatures. The PPD values for summer increased significantly under the future climates, suggesting that discomfort of occupants will rise under climate change conditions.

Table 4. Average hourly indoor air and operative temperatures and PPD values in summer (1st June to 31st August) for the building under different climates.

Description	Indoor air temperature	Operative temperature	PPD-index
1961-1990	24.7	24.8	56.6
1981-2010	24.7	24.7	63.9
RCP2.6-2050s	25.7	25.7	85.0
RCP4.5-2050s	26.5	26.5	88.1
RCP8.5-2050s	27.1	27.1	90.4

The distributions of the summer hourly indoor air temperatures under the different climates are shown in Fig.10 with boxplot. The maximum temperatures range from 30.9 to 33.0°C whilst the minimum temperature remains 22°C under the different climates.

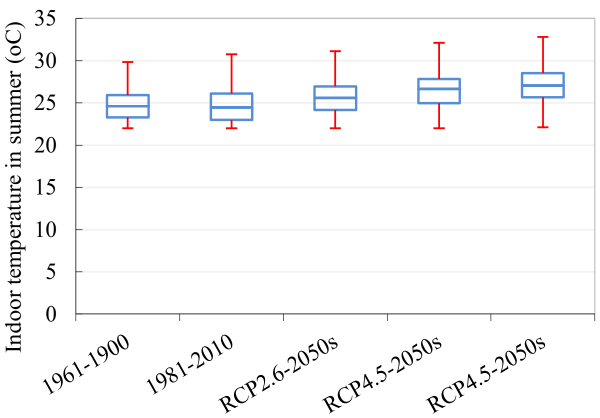

Fig. 10. Distributions of the summer hourly indoor air temperatures under the different climates.

3.3 Adaptation strategies

Fig. 11 shows the number of hours for which the indoor air temperatures of the living area of the building exceeded various overheating thresholds for the long-term historical climate of 1961-1990, for cases with and without overheating control intervention.

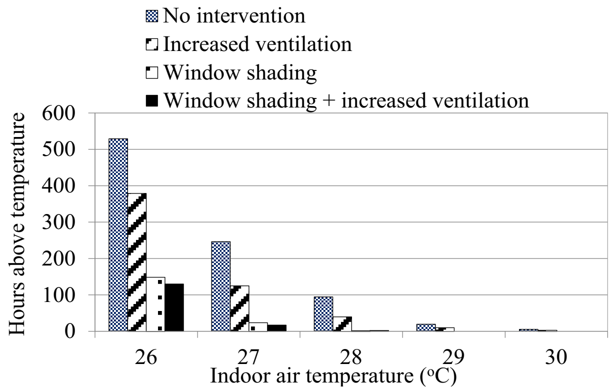

Fig. 11. Hours for which the indoor air temperatures exceeded various overheating thresholds for historical climate (1961-1990).

Fig. 12 and 13 show the number of hours for which the indoor air temperatures exceeded different thresholds for the recent and RCP4.5-2050s climates, respectively. Overheating hours significantly increased under the RCP4.5-2050s compared to the recent climate.

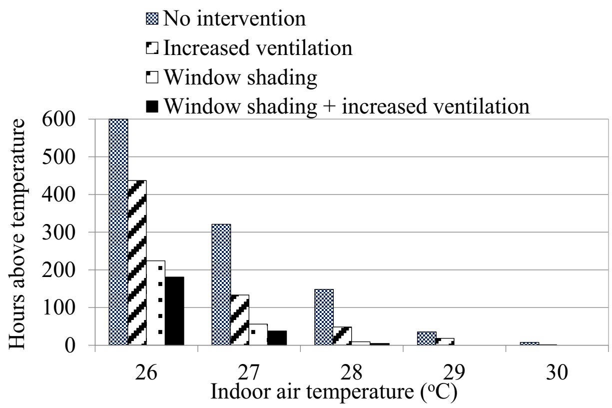

Fig. 12. Hours for which the indoor air temperatures exceeded various overheating thresholds for recent climate (1981-2010).

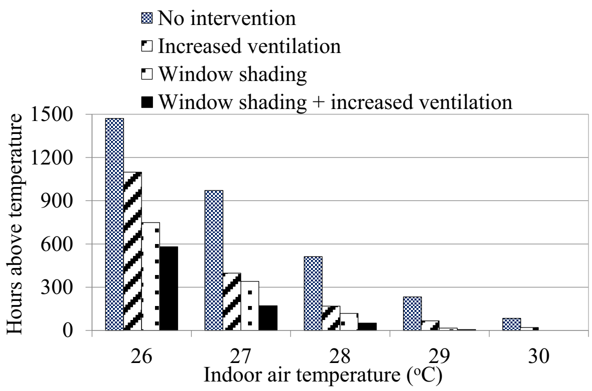

Fig. 13. Hours for which the indoor air temperatures exceeded various overheating thresholds for the RCP4.5-2050s scenario.

In Table 5, the percentages of the occupied hours with the indoor air temperatures above the various thresholds are summarized for the building under the different climates. The hours with indoor temperatures exceeding the various thresholds increased considerably for the future climates, in contrast to the recent climate. Overall, the overheating control strategies, mainly window shading, significantly reduced the number of hours of discomfort temperatures.

Table 5. Percentage (%) of the occupied hours with the indoor air temperatures above various discomfort thresholds.

Description	% of hours above temperatures				
	26°C	27°C	28°C	29°C	30°C
1961-1990:					
No intervention	9.7	4.5	1.7	0.3	0.1
Increased ventilation	6.9	2.3	0.7	0.2	0.1
Window shading	2.7	0.4	0.0	0.0	0.0
Window shading + increased ventilation	2.4	0.3	0.0	0.0	0.0
1981-2010:					
No intervention	11.0	5.9	2.7	0.6	0.1
Increased ventilation	8.0	2.4	0.9	0.3	0.0
Window shading	4.1	1.0	0.2	0.0	0.0
Window shading + increased ventilation	3.3	0.7	0.1	0.0	0.0
RCP2.6-2050s:					
No intervention	17.0	10.0	5.6	2.8	0.9
Increased ventilation	12.5	4.2	2.0	0.8	0.2
Window shading	7.7	3.5	1.3	0.1	0.0
Window shading + increased ventilation	6.1	2.0	0.5	0.1	0.0
RCP4.5-2050s:					
No intervention	26.9	17.8	9.4	4.3	1.6
Increased ventilation	20.1	7.3	3.1	1.2	0.4
Window shading	13.7	6.2	2.2	0.3	0.0
Window shading + increased ventilation	10.6	3.1	0.9	0.1	0.0
RCP8.5-2050s:					
No intervention	31.7	22.4	13.5	7.7	3.6
Increased ventilation	24.7	11.4	5.8	2.4	0.7
Window shading	19.5	11.3	6.2	2.3	0.3
Window shading + increased ventilation	16.2	6.2	2.7	0.5	0.0

Table 6 summarizes the impacts of the overheating control strategies on different comfort factors including maximum hourly indoor air and operative temperatures as well as PPD in summer, for the living areas of the building. Overall, the comfort factors deteriorate under the future climate conditions compared to the recent or historical climate. Notwithstanding, the indoor comfort factors are improved with the implementation of the strategies. The maximum indoor air temperature is about 31°C under the recent climate, and is reduced 2.5°C with the cumulative implementation of the strategies. In contrast, the maximum indoor air temperature is about 33°C under the RCP8.5-2050s climate, and is reduced 2.7°C with the cumulative implementation of the strategies. The decrease in operative temperatures of the building with implementation of the strategies follows the same trend as the indoor air temperatures. Similar to the impact on the discomfort hours, window shading gave the biggest reduction of the PPD values, improving the comfort conditions.

Table 6. Maximum hourly indoor air and operative temperatures and PPD values in summer for the building under the different climates.

Description	Indoor air temperature	Operative temperature	PPD-index
1961-1990:			
No intervention	30.9	31.1	56.6
Increased ventilation	30.5	30.7	50.2
Window shading	28.2	28.3	15.2
Window shading + increased ventilation	28.1	28.2	15.0
1981-2010:			
No intervention	31.1	31.4	63.9
Increased ventilation	30.1	30.5	48.3
Window shading	28.6	28.8	22.6
Window shading + increased ventilation	28.5	28.7	21.9
RCP2.6-2050s:			
No intervention	32.6	32.8	85.0
Increased ventilation	31.6	31.8	70.6
Window shading	29.8	29.9	38.1
Window shading + increased ventilation	29.4	29.5	32.4
RCP4.5-2050s:			
No intervention	32.9	33.2	88.1
Increased ventilation	31.8	32.0	72.5
Window shading	30.0	30.1	46.0
Window shading + increased ventilation	29.7	29.9	45.5
RCP8.5-2050s:			
No intervention	33.0	33.1	90.4
Increased ventilation	32.1	32.1	79.2
Window shading	30.9	30.9	59.2
Window shading + increased ventilation	30.3	30.3	49.5

The effectiveness of the strategies in reducing the cooling energy demand of the building under the different climates is summarized in Fig. 14. The cooling is via air conditioning, activated only if the other strategies cannot entirely achieve the maximum indoor temperature set-point of 26°C. The cooling loads are reduced between 62-76% with the cumulative implementation of the strategies. The reduction of cooling energy demand for window shading is at least a factor-of-three more than that of increased ventilation. The additional cooling energy benefit achieved when window shading and increased ventilation are combined is marginal compared to when only window shading is implemented. This energy benefit ranges between 0.1 to 0.6 kWh/m^2.

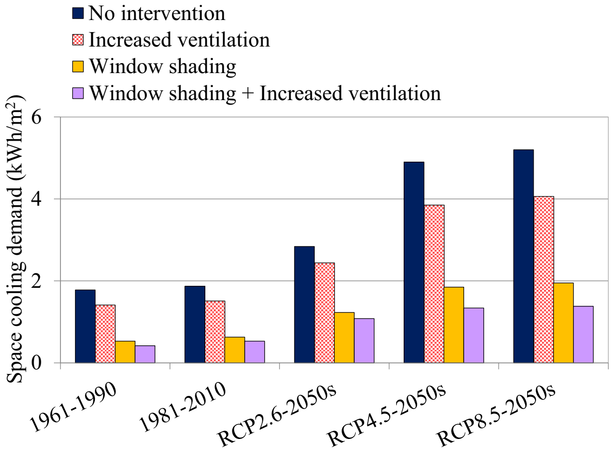

Fig. 14. Space cooling demand of the building with and without overheating control strategies under different climate scenarios.

4 DISCUSSION AND CONCLUSIONS

This paper has examined the implications of projected changes in future climate for energy and indoor thermal comfort performance of a multi-storey residential building in Sweden. The analysis is based on low, medium and high RCP climate change scenarios for the year 2050-2059 time frame. The findings of this study suggest that future climate change will significantly influence energy and indoor climate performance of Swedish residential buildings, and that thermal performance of buildings could be improved with effective overheating control and adaptation strategies.

The analysis show that heating demand would decrease significantly while cooling demand would increase considerably, as noted in previous studies [15, 19, 23-26]. For the building analysed in this study, space heating demand decreased between 15-27% while space cooling demand increased between 60-192% under the projected future climates, compared to the recent climates of Sweden.

Overall, the percentage of total occupant hours with overheating and thermal discomfort increase under the climate change conditions. For the analysed building, indoor temperature and operative temperatures increased for the future climates, compared to the recent climate. Furthermore, the PPD for the building are significantly higher under the future climates compared to the recent climate. However, implementation of control measures as external window shading and increased ventilation significantly reduced overheating and discomfort in the analysed building. This consequently reduced the cooling demand of the building, both under the recent and future climate scenarios.

Profile and magnitude of internal heat gains can significantly impact on indoor air temperatures, overheating risk and cooling loads of buildings [39]. In this analysis, standard electrical appliance and lighting are modelled for the building studied. The implications of improved electrical appliance and lighting which also reduce internal heat gain were not considered. Internal heat gain could be more than halved when household electrical equipment are based on best available instead of standard technologies [33]. However, reduced internal heat gains also result in increased balance of energy that need to be supplied from heating systems. Hence changes in both heating and cooling demands need to be considered in determining the overall implications of reduced internal heat gain from improved electrical equipment.

In summary, this study shows that climate change will significantly affect buildings' energy performance and indoor thermal comfort conditions. This increases the importance of strategies to improve overall energy performance of buildings while minimising overheating risk. Effective adaptation strategies as analysed in this study could significantly improve thermal performance of Swedish buildings under both current and anticipated future climate conditions.

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