CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 7

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 7*. Department of Civil Engineering, Aalborg University.

Climate change impacts on overheating risk and primary energy use for space conditioning of a Swedish multi-story building

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Abstract

In this study we investigate the potential impacts of future climate change scenarios on overheating risk and primary energy use for space conditioning of a newly built multi-story apartment building in Växjö, Sweden. The building is district heated and potentially cooled by stand-alone air conditioners. We consider climate change scenarios for the period 2050-2059, historical climate of 1961-1990 and recent climate of 1996-2005. The climate change scenarios are based on the representative concentration pathways 4.5 and 8.5. We explore the risk of overheating of the building and analyse the impacts of different strategies for overheating control, including increased airing and solar shading besides mechanical cooling. We investigate the implications of different renewable based electricity supply options for space cooling and ventilation of the building. The results show that the space heating demand is significantly reduced and cooling demand is strongly increased for the building with the future climate scenarios. Furthermore the risk of overheating increases under the climate change scenarios. Among the overheating control strategies analysed, solar shading is the single most effective measure, giving the lowest primary energy use for space conditioning. Complementing the electricity from biomass-fired condensing power plants with solar-based electricity reduced the space conditioning primary energy use by 4-9%. Adding increased airing to the control strategies increased the primary energy use.

Keywords - Climate change, space cooling, space heating, energy use, overheating

1. Introduction

A growing body of evidence indicates that the earth’s climate is warming due to increasing emissions of greenhouse gases (GHGs) from anthropogenic activities, including combustion of fossil fuels, industrial process reactions and changes in land-use practices [1]. Global averaged surface temperature has increased by 0.65-1.06 ºC between 1880 to 2012 [1]. Further, 2015 is reported to be the warmest year on modern record, with global surface average temperature about 0.75 ^{o}C above the long-term average for 1961-1990 [2]. Furthermore, global climate change projections suggest that average surface temperature may increase between 2.4 to 3.4°C by the period 2071-2100, compared to the baseline of 1961-1990 [3]. For Sweden, climate change projections suggest mean annual temperature increase of 1.81 to 5.93 °C by 2100, compared to 1961-1990 levels [4].

Buildings contribute substantially to climate change [1], and climate change may have significant effects on buildings, as climate related parameters influence thermal and hygrothermal performances of buildings [5]. The risk of overheating in buildings is increasingly suggested to rise under future climate change scenarios [6, 7]. Overheating risk in buildings is influenced by different factors including building typology and energy efficiency level [6]. In Sweden, the risk of overheating in residential buildings is relatively low under the current climate, but is suggested to increase under projected future climate conditions [6]. The European Union's energy performance of buildings directive highlighted the need to focus on strategies to avoid overheating and to ensure improved thermal performance of buildings [8]. The Swedish National Board of Health and Welfare (SNBHW) reported general guidelines for comfortable indoor climate and suggests that indoor air temperatures in residential buildings should not exceed 24 and 26 °C during winter and summer, respectively [9]. The Chartered Institution of Building Services Engineers (CIBSE) guide on overheating is increasingly cited and 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 [10].

There has been an increasing amount of studies on the implications of climate change for thermal performance of buildings in recent years e.g. [7, 11-16]. Much of current literature has focused on potential changes in overall annual space conditioning energy use of buildings under future climate. Few studies have analysed how peak energy demand of buildings may be altered due to climate change [e.g. 5, 15]. Potential temperature increases are used as proxy to investigate the effects of climate change on building energy use in several studies [11, 16-18]. In general, studies in different countries observed significant changes in building space conditioning energy use, with the dominance of cooling increasing and heating decreasing, under projected climate change conditions [7, 11-16]. However, the overall effect of the projected climate conditions varies significantly for different locations and buildings. In Sweden, few analyses have been reported on the implications of climate change for buildings e.g. [6, 13, 19, 20].

A comprehensive analysis of the implications of climate change for buildings should consider all key building energy sensitive climate parameters. In this study we investigate the potential impacts of different climate change scenarios on overheating risk and primary energy use of a newly built multi-story apartment building in Växjö, Sweden. In our analyses, we explore hourly indoor temperature profiles, as well as the hourly space heating and cooling demands of the building over one year under historical and recent climate conditions and under future climate scenarios based on Representative Concentration Pathways (RCP).

2. Study descriptions

2.1 Case-study building

Our analysis is based on a multi-story apartment building in Växjö, (lat.56°52′N, long.14°48′E), Sweden. The building is a 6-storey concrete frame structure with 24 apartments and was built in 2014. The building's walling system comprise of a layer of cellplast insulation sandwiched between reinforced concrete panels. Figure 1 presents the building's illustration and architectural layout and Table 1 gives its key construction and thermal characteristics.

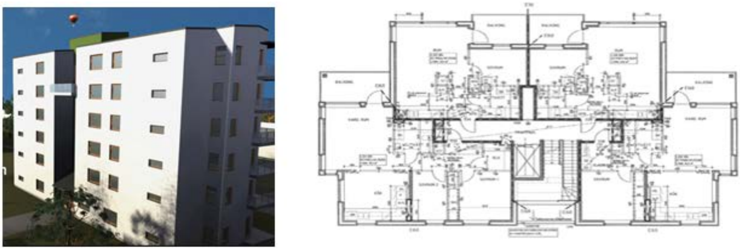


Figure 1. Illustration and ground floor plan of the case-study building.

Table 1. Key construction and thermal characteristics of the building.

Parameter	Detail
Living area (m^2)	1420
Common area (m^2)	266
Total heated air volume (m^3)	4333
Exterior wall area^a (m^2)	1092
Windows area (m^2) [South/West/East/North]	39/161/75/39
Elements U-values (W/m^{2}K):	
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
Mechanical ventilation	Balanced with heat recovery

2.2 Climate scenarios

Table 2 summarizes the climate scenarios considered in this study. As references, building's performance for the climate of Växjö are modelled with long-term historical climate dataset for 1961-1990, noted as climate normal period in Sweden [21]; and with more recent climate dataset for the time period 1996-2005. These are compared with the building's projected performances under climate change scenarios for low (RCP4.5) and high (RCP8.5) radiative forcing levels for 2050-2059.

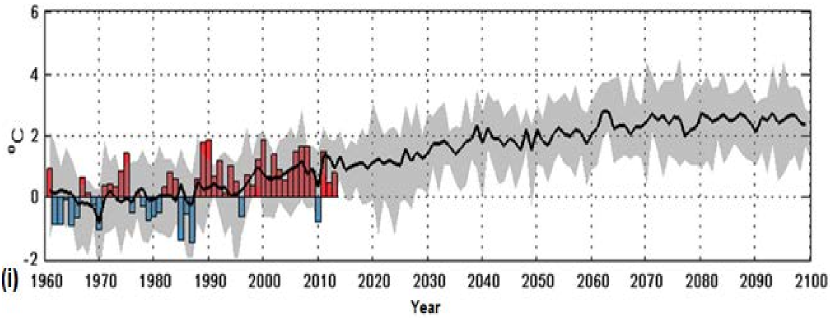
Table 2. Climate dataset considered for the study.

Description	Climate dataset
Historical	Dataset for the period 1961–1990, extracted from the Meteonorm database
Recent	Dataset for the period 1996–2005, from the Meteonorm database
RCP4.5_2050s	Dataset for the period 2050-2059 for RCP 4.5 scenario from RCA4 & HadGEM2
RCP8.5_2050s	Dataset for the period 2050-2059 for RCP 8.5 scenario from RCA4 & HadGEM2

For the 1961-1990 climate dataset, the average mean ambient temperature was 6.4 °C, and the maximum and minimum ambient temperatures were 27.5 and -16 °C, respectively for Växjö. The corresponding values for the 1996-2005 climate dataset are 7, 28 and -17 °C, respectively.

For the climate scenarios for 2050-2059, regionally downscaled data from the RCA4 model based on the HadGEM2-ES global model are used. The RCA4 model is administered by the Rossby Centre of the Swedish Meteorological and Hydrological Institute and provides future climate data at monthly time-step for different climate scenarios for counties and districts in Sweden [22]. Projected climate change for the county of Kronoberg, within which Växjö is situated is used for the analysis. Figure 2 shows projected temperature scenarios for the studied location up to 2100 for the RCP 4.5 and 8.5 scenarios.

(i)



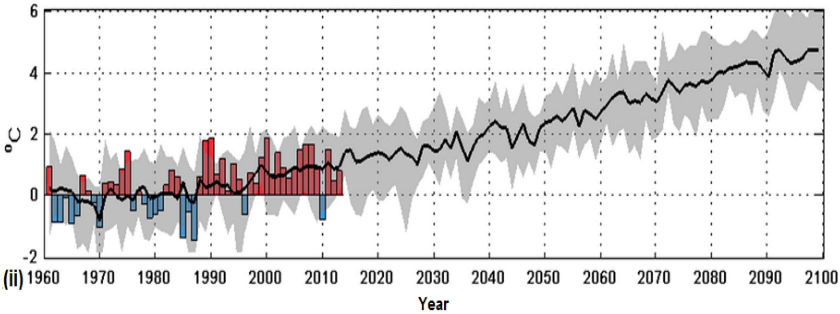


Figure 2. Temperature changes for future climate for the county of Kronoberg, within which Växjö is situated, Sweden, for RCP 4.5 (i) and RCP 8.5(ii). (Adapted from [4])

3. Methodology

3.1 Hourly downscaling of future climate data

Future climate data at smaller time-step than provided by the RCA4 model is required for detailed energy balance calculations. We applied procedures presented by Belcher et al. [23] to downscale future monthly ambient temperature, solar radiation, wind speed and relative humidity data obtained from the RCA4 model to hourly temporal resolution, using the 1961-1990 climate data as baseline. Summarily, the procedures 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 condition. The procedures have been applied in several recent studies, e.g. [14, 24, 25]

3.2 Energy balance and primary energy analysis

Hour-by-hour multi-zone calculations of the final energy balance of the building are conducted for the different climate scenarios for Växjö using the VIP+ software [26]. VIP+ is commercially available whole-building dynamic energy simulation software and is validated by the International Energy Agency’s BESTEST, ASHRAE 140-2007 and CEN 15265. Key input data for the energy balance analysis is presented in Table 3. Presently, cooling load for residential buildings in Växjö is low and cooling is typically induced in summer by shading and effective ventilation strategies. To illustrate the impact of the considered scenarios on cooling requirements for the building, we assume that mechanical cooling systems are used when maximum cooling set-point temperature is exceeded.

The primary energy use for space conditioning of the building is calculated based on district heat from a combined heat and power (CHP) plant and heat-only boilers (HOB) and mechanical cooling by conventional room air conditioners using electricity produced from a stand-alone condensing power plant. All these plants are assumed to be biomass-based.

Furthermore, we illustrate the implications of using solar-based electricity as a complement to biopower during the summer using data from Stoffregen and Schuller [27].

Table 3. Major data for the energy balance calculations.

Parameter	Data / description
Heating set-point temperature	22[a]/ 18[b] °C
Cooling set-point temperature	26 °C
Heat gains from:	
Persons	1.00 W/m^2
Electric related processes	3.05[c] W/m^2
Sun	Calculated
Ventilation rate	0.35 l/m^{2}s
Ventilation fans efficiency	50%
Efficiency of VHR unit	75%
Building occupancy schedule	Occupied all days & hours

[a] Living areas

[b] Common areas

[c] Standard appliances

3.3 Overheating analysis

Overheating risk of the building under the different climate scenarios are analysed using the guidelines provided by the SNBHW [8] and the CIBSE [9]. The annual indoor air temperature profiles are modelled hourly for the building and the percentage of annual operating hours that the temperatures exceed the 26 °C and 28 °C benchmarks suggested by the CIBSE are quantified. The modelled indoor air temperatures are also compared to the SNBHW's recommended indoor air temperature upper limit of 26 °C for summer and 24 °C for winter. Here, we define overheating as an indoor temperature above 28 °C.

Key parameters noted as important in characterizing building' overheating risk, including architectural design, construction, and thermal envelope characteristics of buildings, outdoor climate and internal heat gains, as well as their interactions are analysed in detail. The profile of heat gains from persons and appliances are modelled assuming they are constant over the year. For solar heat gains, seasonal variation is accounted through the hourly climate data used for the simulation. When the climate scenarios are considered the building is simulated with and without measures to control overheating. In addition to the mechanical cooling, configurations of overheating control strategies are analysed, including external shading devices for solar protection and increased airing. The shading devices are assumed to be fitted above the windows and activated when indoor air temperature exceeds 26 °C. The ventilation rate is considered to be doubled to 0.70 l/m^{2}s from the minimum required by the Swedish building code when indoor temperature exceeds 26 °C. We analyse how the different measures and their combination reduce overheating and the need for comfort cooling for the building as well as their impact on energy to operate ventilation fans and pumps.

4. Results and discussion

Table 4 shows annual space heating and cooling demands for the building under the different climate scenarios keeping the indoor temperature between 22 and 26 °C. Space heating demand decrease whilst space cooling demand increase under the future climate scenarios. Figure 3 summarizes the changes in heating and cooling demands of the building relative to the historical dataset for 1961-1990. A 4% decrease in heating demand and a 30% increase in cooling demand are observed with the recent dataset for 1996-2005 compared to the historical dataset. Relative to the historical dataset, heating demands decreased by 22% and by 25% for RCP4.5 and RCP8.5 respectively, by mid-century. Correspondingly, cooling demands increased by 113% and by 126%.

Table 4. Annual space heating and cooling demands (kWh/m^2) for the building with different climate scenarios.

Description	Historical	Recent	RCP4.5_2050s	RCP8.5_2050s
Space heating	59.1	57.0	46.0	44.2
Space cooling	2.3	3.0	4.9	5.2

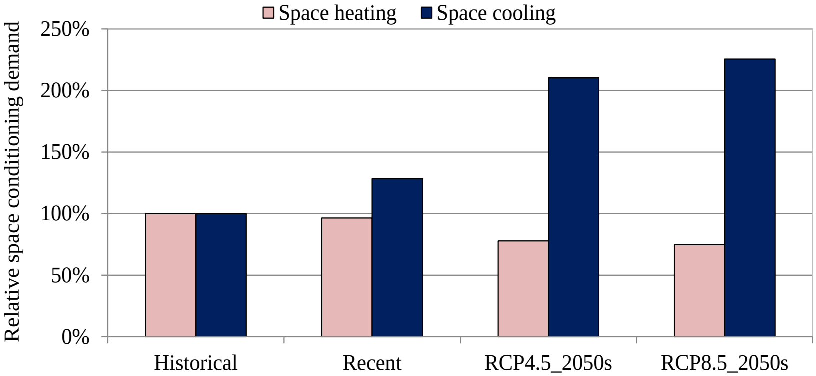


Figure 3. Relative space heating and space cooling demands of the building with different climate scenarios.

The profiles of annual space heating and cooling loads of the building under the different climate scenarios are shown in Figure 4. Peak load for space heating decreased between 6 to 10% under the mid-century climate scenarios while that for cooling increased between 18 to 43%, both relative to the historical baseline.

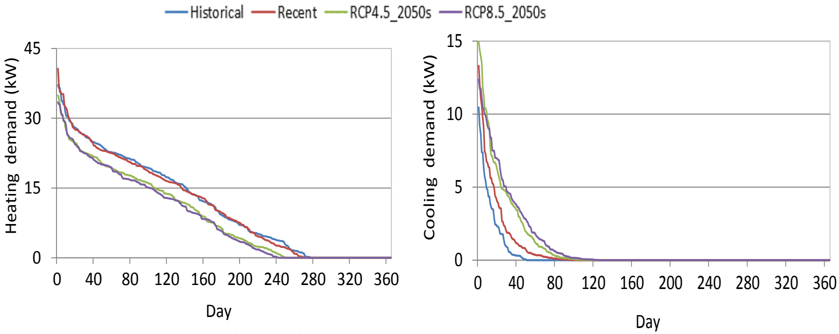


Figure 4. Annual profiles of final space heating (right) and space cooling (left) demands of the building under different climate scenarios arranged in descending order.

Figure 5 shows the modelled annual hourly temperature profiles for the building operated with no intervention for temperature control. The indoor temperature during the winter season, running from December to February, is constant while that for the remaining parts of the year is variable. Predicted average summer indoor temperatures, from 1st June to 31st August, based on annual hourly temperature profiles for the building are summarized in Table 5. Compared to the historical climate, average summer indoor temperatures increased by 0.5, 1.7 and 2 °C for the recent, RCP4.5_2050s and RCP8.5_2050s scenarios, respectively.

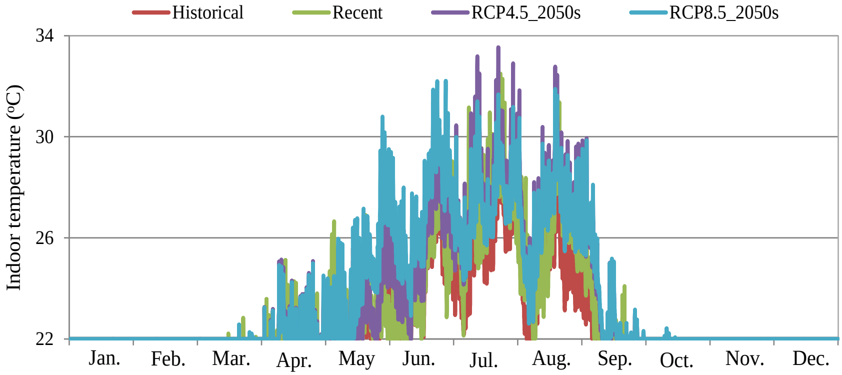


Figure 5. Annual hourly indoor air temperature profile for the building under different climate scenarios with no intervention for temperature control.

Table 5. Average hourly indoor temperatures in summer, from 1st June to 31st August for the building with different climate scenarios.

Description	Historical	Recent	RCP4.5_2050s	RCP8.5_2050s
Temperature (^{o}C)	25.4	25.9	27.1	27.4

Figure 6 shows the proportion of annual operating hours that the predicted indoor air temperatures of living areas of the building exceeds the comfort criteria of 26 ^{o}C and overheating threshold of 28 ^{o}C for the building with and without overheating control strategies. In the no intervention case where the building is operated without measures to control indoor temperature, overheating is observed for all climate scenarios. The effectiveness of the different control measures varies significantly. Increased airing or solar shading prevents overheating for the historical and recent climates. For the future climate scenarios, overheating still occur when increased airing is implemented, but is avoided with solar shading. Overall, shading is the most effective single measure while the combination of solar shading with increase airing significantly reduces the proportion of overheating hours.

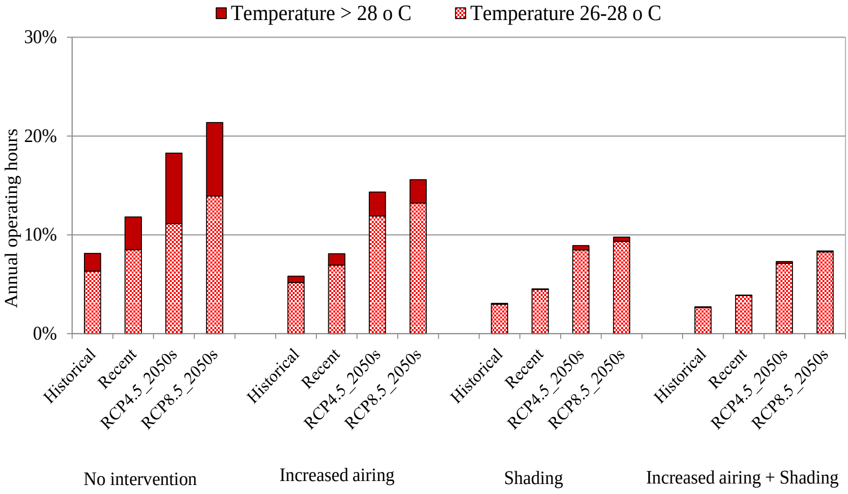


Figure 6. Percentage of operating hours that indoor air temperature of living areas exceeds 26 and 28^{o}C with and without overheating control strategies for different climate scenarios.

The effectiveness of the different overheating control measures in reducing cooling demand of the building are shown in Figure 7, keeping the indoor temperature between 22 and 26 ^{o}C. The combination of increased airing and solar shading reduced the annual cooling demands by 73-78%, compared to the no intervention case. However, the difference in cooling load reduction when only shading is used compared to when shading is combined with increased airing is rather small, amounting up to about 1 kWh/m^2 in the best case.

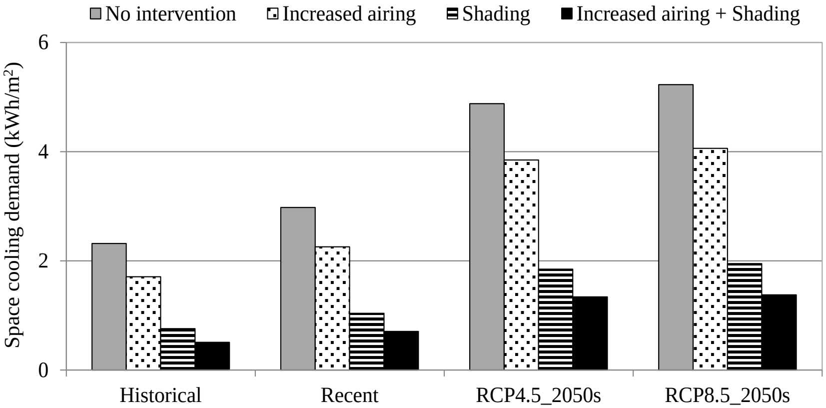


Figure 7. Space cooling demand of the building with and without temperature and overheating control measures under different climate scenarios.

Table 6 shows the annual primary energy use for the building when maintaining indoor temperatures between 22 and 26 °C with different overheating control strategies in combination with air conditioners. Air conditioners are assumed to complement increased airing and shading in cases where the tolerable maximum comfortable indoor temperature is not achievable with only these measures. The primary energy use includes district heat for space heating, electricity for space cooling and for ventilation fans and pumps. The totals for the cases of increased airing and shading include district heat for space heating which is the same with all the measures. The implications of using solar-based electricity during summer are also shown in the Table, besides the base case where electricity is delivered by condensing power plant fired by biomass over the entire year. Overall, the building’s net annual primary energy use decreased under the climate change scenarios. The net annual primary energy use for the building under the recent climate is 1- 2% lower compared to that under the historical climate. Solar shading gives the least net annual primary energy use while increased airing results in the most primary energy use for all the climate scenarios. Compared to the electricity from condensing power plant, using solar-based electricity resulted in net primary energy decrease of 4-9% for the building.

Table 6. Annual primary energy use (kWh/m^2) for the building with different overheating control measures (indoor temperature between 22 and 26 ^{o}C). The numbers *without brackets* is based on biopower while those in brackets consider solar-based electricity as a complement to biopower.

Description	Historical	Recent	RCP4.5_ 2050s	RCP8.5_ 2050s
Complete air conditioning				
Space heating	36.3	35.1	28.3	27.2
Space cooling	2.0 (1.0)	2.5 (1.2)	4.2 (2.0)	4.5 (2.2)
Ventilation	15.4 (13.4)	15.4 (13.4)	15.4 (13.4)	15.4 (13.4)
Total	*53.7 (50.7)*	*53.0 (49.7)*	*47.9 (43.7)*	*47.1 (42.8)*
Increased airing				
Space cooling	1.5 (0.7)	1.9 (0.9)	3.3 (1.6)	3.5 (1.7)
Ventilation	16.0 (13.9)	16.1 (14.1)	16.7 (14.5)	16.8 (14.7)
Total	*53.8 (50.9)*	*53.1 (50.1)*	*48.3 (44.4)*	*47.5 (43.6)*
Shading				
Space cooling	0.6 (0.3)	0.9 (0.4)	1.6 (0.8)	1.7 (0.8)
Ventilation	15.4 (13.4)	15.4 (13.4)	15.4 (13.4)	15.4 (13.4)
Total	*52.3 (50.0)*	*51.4 (48.9)*	*45.3 (42.5)*	*44.3 (41.4)*
Increased airing + Shading				
Space cooling	0.4 (0.2)	0.6 (0.3)	1.1 (0.6)	1.2 (0.6)
Ventilation	15.7 (13.7)	15.8 (13.8)	16.1 (14.1)	16.2 (14.1)
Total	*52.4 (50.2)*	*51.5 (49.2)*	*45.5 (43.0)*	*44.6 (41.9)*

5. Conclusions

In this study, the trends in primary energy use over a year for space conditioning and the risk of overheating of a Swedish residential building under different climate scenarios have been explored. Furthermore, the effectiveness of different overheating control strategies and the implications of using solar-based electricity as a complement to electricity from biomass-fired condensing power plants during summer for cooling and ventilation have been investigated. The analysis showed significant changes in thermal performances of the building for the projected future climate, relative to the historical and recent climates. Heating demand decreased significantly while cooling demand and overheating risk increased considerably with the future climate scenarios.

Among the overheating control alternatives analysed, solar shading is the single most effective measure, giving the lowest primary energy use of all combinations. Implementing solar shading prevents nearly all overheating for the building for the future climate scenarios. The differences in primary energy use for the overheating control strategies are modest with the historical and recent climates but significant with the future climate scenarios. The primary energy use for space conditioning of the buildings under the recent climate and future climate scenarios are reduced between 2 and 4 kWh/m^2 when solar-based electricity is used as complement to electricity from biomass-fired condensing power plants during the summer period.

This study shows that strategies to reduce space cooling demand while minimising overheating risk will become increasingly important for Swedish buildings under future climate scenarios. Efforts to improve energy performance of Swedish buildings for future climate may address measures to avoid overheating and the need for active space cooling systems.

Acknowledgment

We gratefully acknowledge the financial and technical support from the Municipalities of Växjö and Ronneby (Cefur) and the Swedish Energy Agency. The Swedish Meteorological and Hydrological Institute is gratefully acknowledged for providing the data for the future climate scenarios

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