Velashjerdi Farahani, Azin; Jokisalo, Juha; Korhonen, Natalia; Jylhä, Kirsti; Kosonen, Risto; Lestinen, Sami

Performance assessment of ventilative and radiant cooling systems in office buildings during extreme weather conditions under a changing climate

Published in:
Journal of Building Engineering

DOI:
10.1016/j.jobe.2022.104951

Published: 01/10/2022

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

Journal of Building Engineering 57 (2022) 104951

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Performance assessment of ventilative and radiant cooling systems in office buildings during extreme weather conditions under a changing climate

Azin Velashjerdi Farahani [a,*], Juha Jokisalo [a,c], Natalia Korhonen [b], Kirsti Jylhä [b], Risto Kosonen [a,c,d], Sami Lestinen [a]

[a] Department of Mechanical Engineering, Aalto University, Espoo, Finland
[b] Weather and Climate Change Impact Research, Finnish Meteorological Institute, Helsinki, Finland
[c] Smart City Center of Excellence, TalTech, Tallinn, Estonia
[d] College of Urban Construction, Nanjing Tech University, Nanjing, China

A R T I C L E I N F O

Keywords:
Dimensioning cooling power
Design outdoor conditions
Climate change
Commercial buildings
Radiant cooling panel
Variable air volume system

A B S T R A C T

The buildings' HVAC system design and indoor conditions are affected by climate change. This study aimed to investigate the effects of climate change on office buildings' cooling system design and indoor temperature conditions in the Nordic cold climate. Thus, two types of mechanical cooling systems, the all-air (ventilative) and the air-water (radiant), are designed in a new office building by using new cooling design days (1% risk) of the current and future climate of southern Finland. Moreover, dynamic simulations of energy and indoor conditions are performed using different average and extreme climate scenarios. The results showed that the dimensioning cooling power demand with the current climate design day (1% risk level) in the all-air system is higher than in the air-water system by about 18% and it increases significantly when using future climate design days depending on the climate scenarios. The annual maximum cooling power demand in the current and future average climate is below the current climate dimensioning power for both systems. While during extreme weather conditions of the current and future climate, it is higher than the current climate dimensioning power for both systems. Despite the increase in cooling power demands, the dimensioned cooling system using the current climate design day can provide a thermal comfort level of category I of EN16798-1 in all the spaces during the current and future average climate, and category II during the current and future extreme weather conditions. Thus, ventilative and radiant cooling systems equally perform under a changing climate.

1. Introduction

Climate change and increasing ambient temperature have been a growing concern. Each of the last three decades has been warmer at the Earth's surface than any preceding decade since 1850 in the Northern Hemisphere [1]. The global average combined land and ocean surface temperature was 0.99 [0.84 to 1.10] °C higher in 2001–2020 than in 1850–1900 [1]. This rise may affect the frequency of heatwaves which have increased in large parts of Europe [1–3] and are associated with increasing heat-related mortality [4]. Thus, it

* Corresponding author.
E-mail address: azin.velashjerdifarahani@aalto.fi (A. Velashjerdi Farahani).

https://doi.org/10.1016/j.jobe.2022.104951
Received 11 March 2022; Received in revised form 19 May 2022; Accepted 9 July 2022
Available online 19 July 2022

is likely that e.g. naturally ventilated buildings will face overheating in the summer, whereas cooling energy demand will be increased in buildings with mechanical cooling systems [5]. On the other hand, the building sector is one of the main contributors to energy use and greenhouse gas emissions. As buildings are responsible for 40% of the energy consumption and 36% of greenhouse gas emissions in Europe [6]. In 2019, global direct and indirect emissions from non-residential buildings increased by about 55% compared to 1990 [7]. Thus, buildings are at the forefront of the climate change challenge.

Based on the vast body of literature, the severity of the impact of climate change on energy use in office buildings is unquestionable. Cellura et al. [8] examined different climate change models and found an overall increase in total energy consumption with a relative decrease in heating demand and an increase in cooling demand by 2090 in Southern Europe. Nguyen et al. [9] compared the optimization models as a collection of solutions to the existing buildings. The results showed that the existing building will have a 7.2%–12.3% increase in total energy consumption and a significant increase in overheating period in the future. Although the use of optimization in the building design and operation phase helps reduce energy consumption and overheating in the current climate, it can not mitigate the effects of climate change. Another study in the cold climate of Canada by Berardi and Jafarpur [10] showed an average decrease of 18%–33% for the heating energy use, and an average increase of 15%–126% for the cooling energy use by 2070, depending on different climatic zones of Canada. This impact is not just because of the rise of outdoor temperature, but changes in enthalpy and its effects on the dehumidification and cooling power demand must be considered for predicting cooling energy. A study by Mingcai et al. [11] in China, showed that building cooling energy consumption is affected by different climate factors in different climate conditions under a changing climate and changes in humidity must be considered rather than just temperature.

The selection of outdoor design conditions is an important factor in determining the building cooling loads and cooling power required for air conditioning equipment [12,13]. ASHRAE Standard 169 [14] provides a variety of climatic information over the world based on the average conditions during the past 25 years for the design, planning, and sizing of buildings' energy systems and equipment. However, Xu et al. [15] showed that the outdoor design conditions should be regularly updated to reflect the climate change effects on heatwaves. Kajtar and Voros [16] found that the cooling system designed with weather data recommended by the standards has a high risk to be undersized in warm summers. Another study by Chen and Yu [17] proposed a statistical method for determining solar radiation, and outdoor dry-bulb and wet-bulb temperatures selected for design conditions in Hong Kong. Their results showed that the peak cooling load with the traditional design weather data recommended by the standards is always much higher than the results with their proposed design weather data. Research by Yu et al. [18] investigated climatic influences on chiller systems in commercial buildings in Hong Kong. Based on the results a 3.9–4.2% extension in the cooling capacity should be considered for air-cooled and water-cooled chillers to meet the increasing cooling demand over their 15-year functional life. Yau and Hasbi [19] found that climate change may affect the system design as the maximum cooling load may increase by 3–12% in 2020, 2050, and 2080 respectively compared to 2000. Based on the literature, the typical test reference year datasets (aiming to describe a 30-year average climate) are suitable for energy and indoor temperature calculations. While due to climate change, variations between the years and the probability of summer heatwaves occurrence are increasing, and in average climatic data, these extreme weather conditions are hard to be considered. Thus, determining the design weather conditions considering the effects of climate change is an important issue.

On the other hand, novel heating, ventilation, and air conditioning (HVAC) control strategies may help climate change mitigation in office buildings. Sánchez-García et al. [20] examined the application of an adaptive comfort control mode in mixed-mode office

Table 1
The summary of the reviewed literature.

Main objective	Climate	Climatic data	Studied factors
Office buildings' energy consumption	• Cold (Canada) [10, 11] • Moderate [11] • Mediterranean [8] • Subtropical [9] • Hot [11]	• Current climate • Future climates	• Heating energy [8–10] • Cooling energy [8–11] • Overheating risk [9]
Outdoor design conditions	• Moderate [16] • Continental [15] • Subtropical [17,18] • Tropical [19]	• Current Climate • Future climates	• Sequences of coincident design weather parameters [17] • Climatic influences on chiller capacity [18] • Optimal period of record for outdoor design conditions [15] • Dimensioning risk level [16] • Cooling load [19]
Cooling systems operational settings	• Cold (Canada) [21, 22] • Moderate [22] • Mediterranean [20] • Subtropical [23] • Hot [22]	• Current Climate • Future climates	• Setpoints [21,22] • Control systems [20] • COP of chiller plants [23]
Different cooling system performance	• Moderate] [27] • Mediterranean [25] • Tropical [24]	• Current climate	• Air-water systems (radiant panels) [24,25,27] • Air-water systems (thermal activated building systems) [26] • All-air systems [24–27]

buildings in Spain. The reduction of the total energy demand caused by the utilization of adaptive comfort control mode changes from 31.0% currently to 39.1% in 2080 weather data. Jafarpur and Berardi [21] showed that adjusting the room air temperature setpoints can decrease the annual total energy demand by up to 10% in the cold climate of Canada. Wang et al. [22] investigated the effects of adjustment of thermostat setpoints and operation hours of variable air volume (VAV) ventilation systems as well as mixed-mode ventilation on mitigating the climate change impact in office buildings of 5 cities in the USA. The measures were effective in reducing total annual energy consumption in the current climate but were not enough to counteract climate change. However, mixed-mode ventilation was the most effective mitigation measure for all the cities. Wan et al. [23] analyzed potential climate change mitigation measures of the chiller plant as well as the building envelope, internal condition, and lighting load density. They showed that the coefficient of performance (COP) of the chiller plant should be improved from the current minimum requirement of 4.7 to at least 5.5 to minimize the impact of climate change.

Investigating the difference in system performance is an important issue for understanding the effects of climate change in office buildings. Khan et al. [24] found that the air-water system, where the radiant cooling ceiling was implemented, was 17.5% more efficient than a conventional all-air system, where all cooling power was covered with ventilation, in India. A study by Pieska et al. [25] indicated that the radiant cooling system uses 40% less energy than the all-air system despite the condensation risk. Rijksen et al. [26] found that 50% of reductions in the cooling capacity for a chiller can be achieved using thermal-activated building systems (TABS) which is a type of air-water system. Research by Ning et al. [27] showed that the peak cooling load is 16% larger and the operative temperature is about 1.1 °C lower with the radiant cooling panels combined with a dedicated outdoor air system than in all-air systems.

An overview of the reviewed literature is presented in Table 1.

Despite the extensive studies on the effects of climate change in office buildings, more work for office buildings in cold climates is needed to investigate the effects of heatwaves in changing climate. This research gap is summarized for future consideration as follows:

- Most studies have focused on the heating and cooling energy demand, while climate change affects the power demand of cooling systems, as well. Thus, it is important to analyze the effect of changing climate conditions on dimensioning of the cooling systems.
- The effect of climate change and associated heatwaves on cooling power demand and indoor thermal conditions need to be considered.
- Adaptation and mitigation strategies in HVAC system design have been investigated in previous studies. However, the performance of different HVAC systems (all-air and air-water) under a changing climate still needs to be analyzed and discussed.
- The current analysis is mostly done in warm and hot climates, while the increases in outdoor air temperature are more rapid in cold Nordic countries. Thus, investigating the effects of climate change in office buildings in cold climates needs more work.

Analyzing the effects of climate change on HVAC system design and operation is necessary. This paper attempts to deepen the understanding of the design and operation of mechanical cooling systems including all-air (ventilative cooling) and air-water (radiant cooling) systems under the impact of climate change. The novelty of this paper is a particular analysis of the dimensioning of the cooling systems in office buildings considering the changing climate and its associated heatwaves. To dimension the required cooling power, the new design days of the current and future climate of Finland are used for the simulations. Moreover, the peak power and energy demands for all-air and air-water cooling systems of an office building are simulated and compared using the current and projected future (2050) datasets of average climate. Finally, simulations are made for extreme weather conditions, using the actual climate dataset of the hot summer of 2018 in the cold climate of Finland, and its projected counterpart in the future under two global emission scenarios.

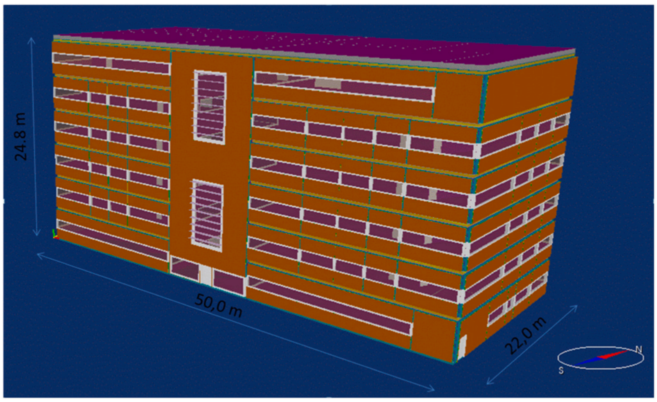

Fig. 1. The geometry of the example building.

2. Materials and methods

2.1. Building description

2.1.1. Studied building

The example building of this study is a six-story office building located in Helsinki, southern Finland. This example building has been used to show the cost optimality of building regulations for the European Commission [28]. The facade with the largest windows fronts south. The geometry of the building is shown in Fig. 1. The heated net floor area of the buildings is 5744 m^2. It is assumed that the example building is surrounded by similar buildings as is shown in Fig. 2. The layout of all six floors is the same. There are different room types, meeting rooms, single office rooms, and an open layout office on each floor as well as service spaces like restaurants and toilets. The layout of the west side of the middle floor is shown in Fig. 3. The office rooms and meeting rooms on the east side are symmetric to the west side of the building. To simplify the analysis, only the west side is simulated. The simulated zones are multiplied by the number of all similar zones in the building.

The building represents the new office buildings. The window to wall ratio is 50%. The construction properties of the building including the U-values and window properties are reported in Table 2 [28]. Manually controlled blinds between the outer window panes are used except for the windows of the atrium.

The building is occupied from 8 to 17 on weekdays and the total number of occupants is 307 with an average occupancy density of 1 per 20 m^2. The activity level of 1.2 MET and adjustable clothing level (0.85 $\pm$ 0.25 CLO) are used. The corresponding occupancy profiles for each kind of room are shown in Fig. 4. Profiles number 1–3 are used in different meeting rooms, number 4 in different office rooms, and number 5 in the open offices. These are similar to the profiles used for showing the cost optimality of building regulations for the European Commission [28].

The total annual electricity consumption of office equipment is 22.4 kWh/m^2 [29] per heated net floor area. The electric power of the appliances (W/m^2) is assumed to be evenly distributed by the floor area of all the simulated zones including office and service spaces in the building, and the appliances are used based on the occupancy profile.

The total annual electricity consumption of indoor lighting is 18.6 kWh/m^2 [29] per total heated net floor area of the building. The electric lighting power (W/m^2) is assumed to be evenly distributed by the floor area of all the simulated zones in the building and the lighting equipment is used on weekdays based on the occupancy profile.

2.1.2. HVAC system description

The heating system of the building is district heating (DH). The efficiency of the heat exchanger in the DH substation is 97%. Space heating is carried out by low-temperature water radiators (45/35 °C) and the heat distribution efficiency is 90%. The temperature setpoint of the room air temperature is 21 °C in all the spaces and is controlled by an ideal thermostat radiant valve.

All-air and Air-water systems are commonly used in the office buildings of Nordic countries. These two systems are fundamentally different in the breakdown of sensible and latent loads and can perform differently through climate change. Thus, these two systems are analyzed. The air-water system can have non-condensing (e.g., radiant panels) and condensing units (e.g., fan coils) in the market. Since the non-condensing ones are more challenging regarding the climate change impacts, the focus of this study is on radiant panels which are commonly used in office buildings in Finland.

The ventilation system of the building is a mechanical balanced variable air volume (VAV) system with heat recovery. Two air handling units (AHU) are installed in the building. The main AHU is used 2 h before and after the normal occupied time, on weekdays from 6 to 19, and the air flow rate is controlled by the CO_2 concentration or room air temperature. The basic AHU with a constant airflow rate is assumed to be running continuously every day including nights and weekends to remove the material emissions [30]. It is a constant air volume (CAV) system.

The properties of the buildings and the HVAC system are assumed to be the same in the simulations of current and future climate conditions to ease the comparison of the results, even if the efficiencies of the systems may improve in the future. Therefore, the

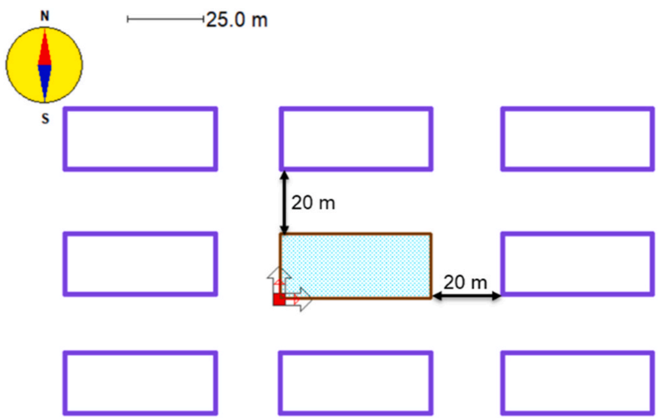

Fig. 2. The surrounding buildings. The example building is shown with a dotted pattern.

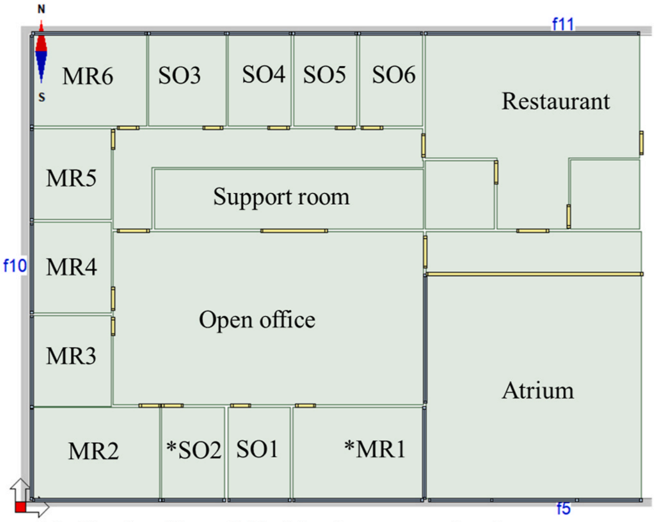

Fig. 3. The layout of the west side of the middle floor.

Table 2
The construction properties of the example office building.

Envelope properties	U value (W/m^{2}K)	External wall 0.17 Roof 0.09 Base floor 0.17
	Air Leakage q_{50} (m^3/h,m^2)	2
Window properties	U value (W/m^{2}K)	1
	Direct solar transmittance (ST)	0.3
	Total solar heat transmittance (g)	0.35
	External shading	Window indentation 5 cm
	Integrated shading	Manually controlled blinds between the outer window panes, according to the occupancy profile and the intensity of solar radiation (>100 W/m^2).
	Window opening	None

coefficiency of performance (COP) of the chiller is assumed to be 3 and constant in all the cases. The dimensioning cooling power demand of the chiller is defined in the results (section 3.1.1).

Two sets of simulations are conducted in this study: the dimensioning cases of the cooling power demand, and second, the annual cases for energy consumption and thermal comfort analysis (see Sec. 2.5 for details). The properties of the HVAC system in these simulation cases are as follows:

A. HVAC system in dimensioning cases: In this study, two different ventilation and cooling systems: 1) all-air system (VAV ventilative cooling) and 2) air-water system (the major part of cooling is provided by radiant panels and airflow rate is for the dehumidification in AHU), are dimensioned using the current and future climate cooling design days. The properties of the systems for the dimensioning analysis are shown in Table 3.

The supply air temperature after the cooling coil of both AHUs is 13 °C and it is supplied at 14 °C in the rooms due to the fans and ductwork pick-up heat. In both systems, there is a basic CAV AHU available in all the spaces with 0.15 L/s,m^2 constantly during the whole day. Additionally, the main VAV AHU is controlled by the CO_2 concentration and air temperature of the spaces in the all-air system, and by the CO_2 concentration of the spaces in the air-water system. There is no night flush ventilation used in these dimensioning cases because the night temperature is high and it does not provide much cooling power.

The space cooling of the air-water system is provided by radiant cooling panels on the ceiling. The capacity of the panel is 60 W per m^2 of the panel area. In the design conditions, the difference between the average room air temperature and average water temperature (inlet and outlet water) is 8 °C. The temperature difference between the inlet and return water at design power is 2 °C (16–18 °C). The required cooling power of radiant panels for each room is sized and reported in the Results section.

B. HVAC system in annual simulation cases: In addition to the cases for dimensioning, the example building is simulated using two types of annual weather datasets for the current and future climates of Finland (Sec. 2.2). The properties of the systems in the annual cases are the same as in the dimensioning cases, except for the cooling setpoint and the usage of the night flush ventilation.

In these annual simulations, the cooling setpoint in all the spaces of the building is defined based on the outdoor 24-h sliding average temperature [31]. Fig. 5 shows the room air temperature setpoint as a function of the outdoor 24-h sliding average. Night flush

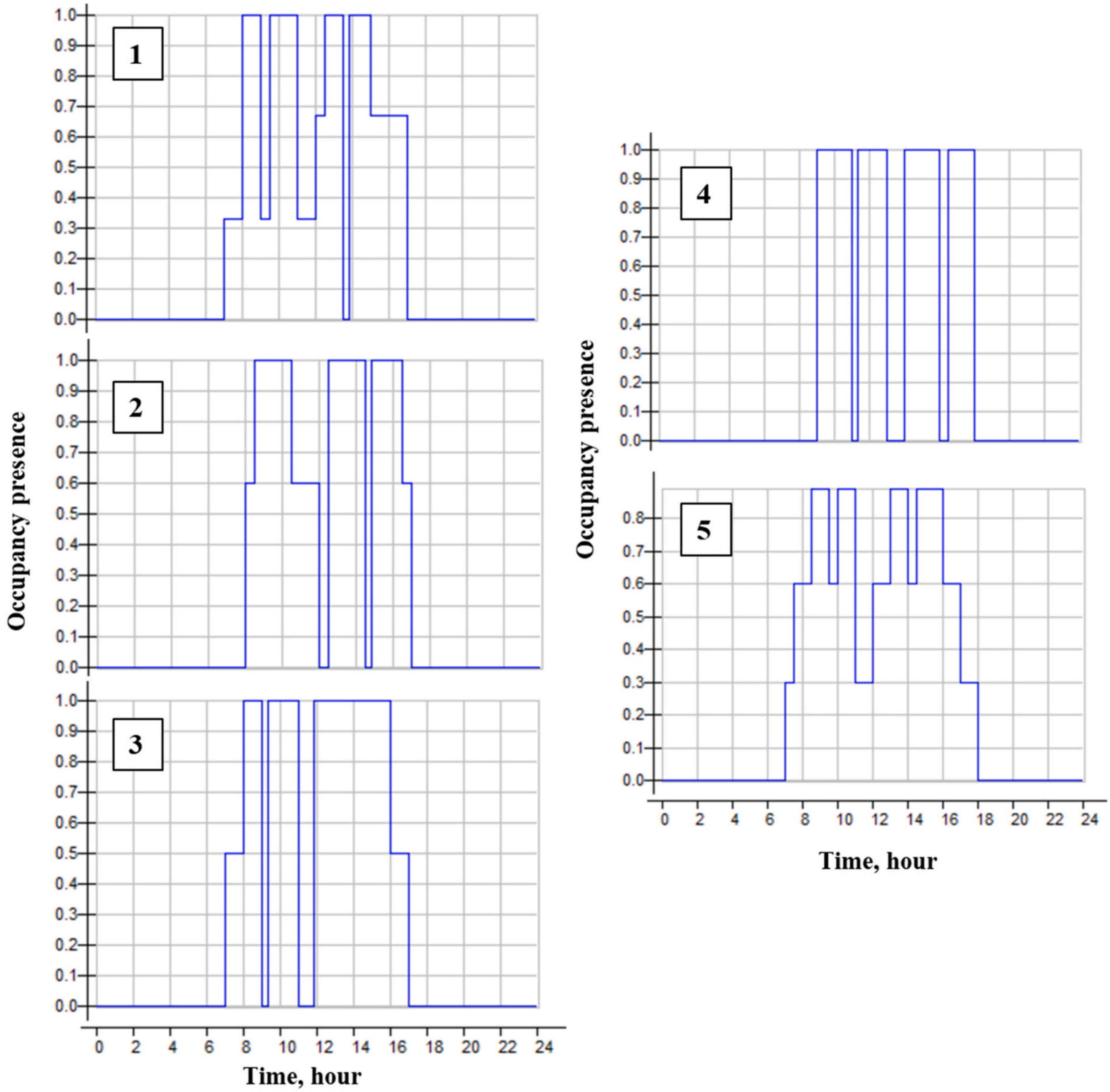

Fig. 4. The occupancy profiles of office rooms and meeting rooms. The values (0, 1) of the vertical axes are the ratio of the number of present occupants to the maximum number of occupants defined for the spaces.

ventilation by the main AHU is in use in both all-air and air-water systems from 22 to 6 on weekdays if the outdoor air temperature is above 12 °C, the outdoor air temperature is at least 2 °C below the return air temperature, and the return air temperature is above 23 °C.

2.2. Climatic data

Meteorological observations at the Helsinki-Vantaa weather station in the Helsinki metropolitan area during the period of 1981–2018 were used in this study to represent current climatological conditions in southern Finland. Based on the 30-year period of meteorological measurements, specific weather episodes were selected for dimensioning of cooling (Section 2.2.1). Furthermore, following Farahani et al. [32] two types of one-year datasets were chosen from the meteorological measurements in 1989–2018, one describing typical and the other extreme summertime weather conditions in the current climate of southern Finland (Sections 2.2.2-2.2.3).

For simulations of the example building in an altered climate of the coming decades, the hourly weather datasets describing cooling design days, typical weather conditions, and extreme weather conditions in the current climate were modified to approximate the future. Use was made of output from a large number of climate model runs [33] under two different Representative Concentration

Table 3
The properties of the ventilation and cooling systems in the dimensioning cases.

System	Ventilation		Space cooling	Cooling setpoint
	Main AHU	Basic AHU		
Air-water	VAV: CO2 control Supply air temperature setpoint in the room: 14 °C (No night flush) (6–19 weekdays) • Office rooms: min 1 L/s,m^2 (if CO2 $<$ 600 ppm) max 2 L/s,m^2(if CO2 $>$ 900 ppm) • Meeting rooms: min 1 L/s,m^2 (if CO2 $<$ 600 ppm) max 4 L/s,m^2(if CO2 $>$ 900 ppm)	CAV, 0.15 L/s,m^2	Radiant cooling panels Room units are calculated in the results (3.1.1).	24 °C
All-air	VAV: CO_2 and temperature control Supply air temperature setpoint in the room: 14 °C (No night flush) (6–19 weekdays) Airflow rates are calculated in the results (3.1.1).		-	

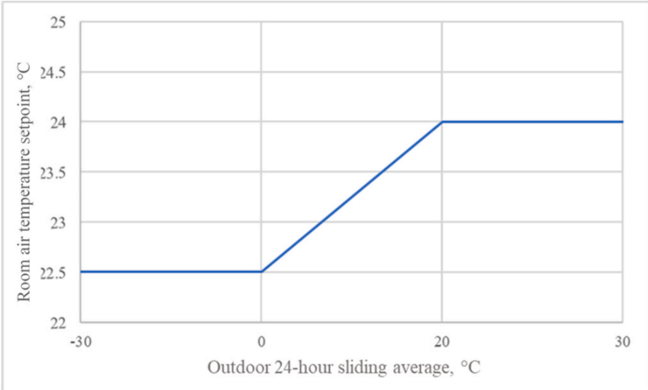

Fig. 5. The setpoint of the room air temperature as a function of outdoor 24-h sliding average temperature for the annual cases.

Pathways (RCPs) of greenhouse gases (GHGs) and aerosols in the atmosphere: RCP4.5 and RCP8.5 [34]. Under the RCP8.5 scenario, the global GHG emissions continue to increase throughout the 21st century, while in the RCP4.5 scenario the emissions start to decline after around 2040. Within a larger set of RCPs, RCP4.5 represents an intermediate scenario whereas RCP8.5 can be regarded as a worst-case scenario. By 2050, the annual mean temperature of Finland is projected to decrease at a rate of 0.42 °C per decade under RCP4.5 and 0.59 °C per decade under RCP8.5. For summer (June–August) mean temperature, the rates of change are 0.34 °C and 0.46 °C per decade, respectively [33].

The hourly weather data sets of the current climate were transformed to represent future climate conditions based on the multi-model mean climate change projections [33,35] using so-called delta change methods [36,37]. For example, the delta-change method applied for the outdoor air temperature took into account both changes in the monthly mean temperatures and changes in the monthly standard deviation of daily mean temperatures. The observed hourly global solar radiation values were simply adjusted based on projected changes in monthly means, while an iterative approach was needed for relative humidity.

2.2.1. *Design weather periods for cooling in the current and future climate*

The new cooling design days for southern Finland (Vantaa in July) have been chosen utilizing SFS-EN ISO 15927-2 standard [38]. The standard presents methods of calculation of external design climate to be used in determining the design cooling load of buildings and the design of air conditioning systems. The standard can be used to define the individual days of hourly or three-hourly data in each calendar month that impose a cooling load likely to be exceeded on 5%, 2%, and 1% of days (risk level). Thus, 1% risk level is with the highest cooling power demand to fulfill the indoor temperature requirements.

In this study, the daily climatic variables (daily mean outdoor temperature °C, daily mean dewpoint temperature °C, daily total global solar irradiation, kWh/m^{2}d) that are exceeded on 1% of days are determined for each calendar month based on 1989–2018

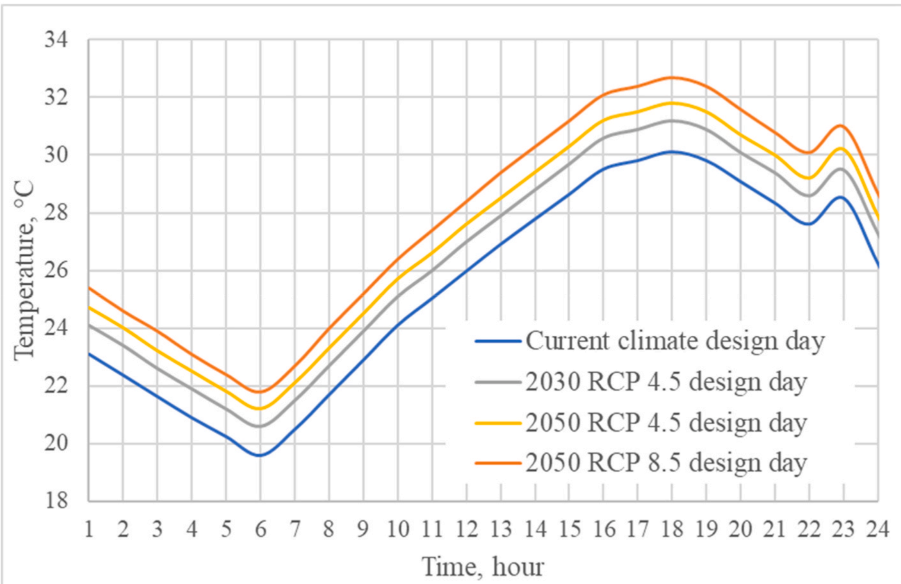

Fig. 6. The outdoor enthalpy in the current and future design days.

weather data. An iterative method of the standard is used to find the most appropriate day for each calendar month. Then the months of summer are compared and the current climate design day is defined with 1% risk level in July for southern Finland which is the highest value of the three aforementioned climate variables.

Moreover, the same day is extracted from the projected future climates under Representative Concentration Pathway 2030 RCP4.5, 2050 RCP4.5, and 8.5. For the future, we considered the years 2030 and 2050 which represent an early and a late time, respectively, in the life span of the cooling system.

Figs. 6 and 7 show the outdoor enthalpy and temperature in the current and future cooling design days (1% risk level), respectively. The maximum outdoor temperature varies from 30.0 °C to 33.0 °C. The minimum outdoor temperature varies from 19.5 to 22.0 °C, which shows that the free cooling capacity of night flush ventilation would be insignificant. The maximum enthalpy is 65 kJ/kg on the current climate design day and it increases up to 72 kJ/kg on the design day of the year 2050 under the RCP8.5 scenario. These values are comparable with earlier scenarios for enthalpy in Vantaa in the future [39,40]. It is worth noting that in other Finnish stations but Helsinki-Vantaa, even higher values of enthalpy than in Fig. 6 have already been observed.

2.2.2. Development of 30 years weather data sets for the current and future climate

In this study, we used six different hourly climate datasets as input for annual simulations. The monthly mean outdoor temperature and global horizontal irradiance of these datasets are shown in Fig. 8.

The test reference year TRY2020 data set represents typical climatic conditions - in terms of outdoor air temperature and global horizontal irradiance, humidity, and wind speed - during the 30-year periods of 1989–2018 (midpoint 2004). The selection of TRY2020 was based on a standard method [38] with some modifications [36,41]. The hourly TRY2020 dataset was based on continuous measurements of global and diffuse solar radiation, interpolation of 3-hourly observations of air temperature, humidity, and wind speed, and recordings of the lowest and highest temperature of each day. In TRY2020, the average monthly mean temperature ranges between −4.5 °C in February and 17.4 °C in July, and the average monthly mean global horizontal irradiance is between 6 W/m^2 in December and 235 W/m^2 in July.

The TRY2050 RCP4.5 and TRY2050 RCP8.5 datasets represent two different future average climate scenarios during the 30-year period of 2035–2064 (midpoint 2050). In the TRY2050 RCP4.5, the projected increase in the monthly mean temperatures for 2050, relative to TRY2020, ranges from 1.5 °C to 2.3 °C, see Fig. 8. In TRY2050 RCP8.5, the monthly mean temperatures are 1.9–3.2 °C are higher than in TRY2020. Under both RCP4.5 and RCP8.5 emission scenarios, due to changes in cloudiness and aerosol particle concentrations [33], the monthly mean global horizontal irradiance is projected to slightly decrease during November–March and to increase during April–October.

2.2.3. Extreme weather conditions (hot summers) for the current and future climate

Here a heatwave is defined as a period of days with the daily maximum outdoor temperature above 25 °C [42]. Table 4 lists the five longest continuous heatwaves at the Helsinki-Vantaa weather station during the summers 1990–2021. The top longest heatwave lasted for 25 days and took place in July–August 2018. During it, the highest hourly temperature was 30.8 °C and there were five tropical nights, i.e., nights in which the nighttime (9 p.m.–9 a.m.) minimum temperature exceeded 20 °C [43]. This 25-day long heatwave in July–August 2018 [44] led to about 380 additional deaths in Finland [45]. In Helsinki, the number of attributable deaths was about 75, corresponding to the heat-related mortality of almost 12 per 100000 inhabitants, which was about 2.2 times higher than in the

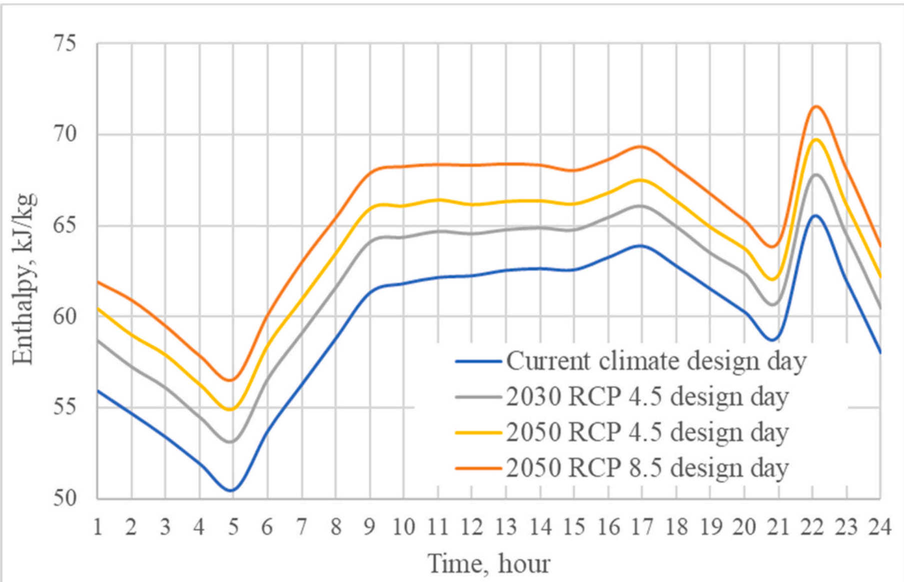

Fig. 7. The outdoor temperature in the current and future design days.

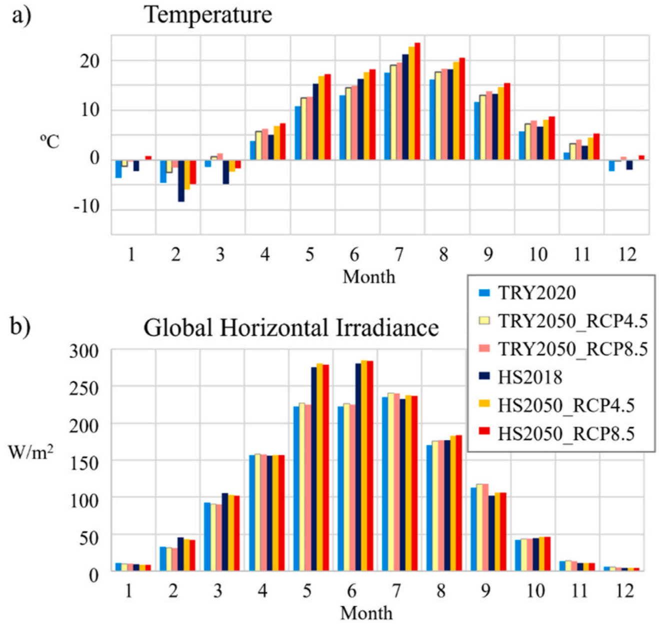

Fig. 8. Monthly mean (a) temperature and (b) global horizontal irradiance at Helsinki-Vantaa in the test reference year (TRY2020), in test reference year projected for the year 2050 under the RCP4.5 scenario (TRY2050 RCP4.5), in test reference year projected for the year 2050 under the RCP8.5 scenario (TRY2050 RCP8.5), during the year 2018 (HS2018), the year 2018 transformed to represent climate conditions around the year 2050 under the RCP4.5 scenario (HS2050 RCP4.5), and the year 2018 transformed to represent climate conditions around the year 2050 under the RCP8.5 scenario (HS2050 RCP8.5).

Table 4
Top 5 longest periods of daily maximum temperature above 25 °C at the Helsinki-Vantaa airport during summers 1990–2021.

Rank	Length (days)	The Period
1	25	12.7.-5.8.2018
2	20	4.-23.7.2010
3	16	3.-18.7.2021
4	14	18.-31.7.2014
5	10	7.-16.7.1994

surrounding region [46]. The dataset HS2018 represents the year 2018 with this severe heatwave in July–August and the record warm July [47] with the monthly mean temperature of July being 3.8 °C higher than in the TRY2020 (Fig. 8). Unlike the TRY2020 dataset, HS2018 was based on hourly, rather than 3-hourly, observations of air temperature, humidity, and wind speed.

The severity of a heatwave like the one in 2018 in the future climate was assessed by modifying the hourly weather observations during the year 2018 (the HS2018 dataset) with the aid of the delta change methods and the climate change projections, as discussed above. In the modification, it was assumed that the hot summer (HS2018) could have occurred in any summer of the period 1989–2018. The resulting weather files represent climate conditions around the year 2050 under the RCP4.5 scenario (the HS2050 RCP4.5 dataset) and the RCP8.5 scenario (HS2050 RCP8.5).

In the HS2050 RCP4.5 (HS2050 RCP8.5) dataset the highest hourly temperature was 32.0 °C (32.9 °C), the number of tropical nights was 15 (17) during the heatwave in July–August, and the monthly mean temperature of July increased by 1.5 °C (2.3 °C) relative to the year 2018.

2.3. Building simulation tool

IDA Indoor Climate and Energy (ICE) tool was used for the whole building's hour-by-hour multi-zone simulations of the cooling power, energy demand, and indoor conditions of the building [48]. Thermal envelope, HVAC systems, operational and occupancy schedules of the building, and their interactions with outdoor climate variables are simulated in the software. The validation of IDA ICE has been done in many studies e.g., Refs. [49–51]. Moreover, IDA ICE has been under benchmark testing and validated for indoor temperature calculations based on the CEN standard [52,53].

2.4. Target values for indoor temperature

To analyze the indoor air temperature in the office spaces, different categories of thermal environments recommended in EN 16798–1 [30] are used as the target values. The European standard specifies the indoor environmental parameters, which have an impact on the energy performance of the buildings. The recommended range of indoor temperatures during the cooling season for the three categories is shown in Table 5. In this study, a target value of 25 °C is chosen for the recommended upper limit of indoor temperatures, following the Finnish indoor temperature classification [31] which is voluntary based.

2.5. Simulation cases

There are two sets of simulation cases in this study. The first set consists of four dimensioning cases of the required cooling power, and the second set includes altogether six annual cases for energy consumption and thermal comfort analysis. This process is presented in Fig. 9. The properties of the building and its systems are as described in Section 2.1. In the dimensioning cases, the aim is to dimension the cooling power demand at the room and the whole building levels. Thus at the room level, the sensible dimensioning power demand of the radiant cooling units in each room is calculated for the air-water system, and the required airflow rates of each room are analyzed for the all-air system. Consequently, at the building level, the maximum cooling power needed in the chiller to cover sensible space cooling power demand and dehumidification demand of AHU are analyzed. The maximum total cooling power demand of all-air and air-water systems are compared, as well. As input weather data, cooling design days (1% risk level) are used in the dimensioning cases (Table 6).

In the annual cases of energy consumption and thermal conditions analysis, the building is equipped with the designed cooling systems that are based on the current climate cooling design day (1% risk level) and detailed in the dimensioning cases described above. Input weather data to the annual simulations is provided by the current and future test reference years (TRY2020 and TRY2050) and the current and future extreme weather conditions (HS2018 and HS2050) (Table 6). The acronyms of the climatic input datasets for the simulations are given in Section 2.2.

3. Results

3.1. Cooling power demand and indoor climates

3.1.1. Current and future design conditions

A. Dimensioning of the room level systems using the current design day (1% risk level): The sensible cooling power demand of radiant panels with the air-water system and the required supply airflow rates for each space with the all-air system are simulated for each room using the current cooling design day (1% risk level). The results of meeting rooms and single office rooms having the lowest and the highest sensible cooling power demand are shown in Table 7. The HVAC properties are as described in Table 3. The dimensioning power demand of the radiant panel of the air-water system and airflow rates of the all-air system are defined in a way that the room air temperatures are always lower than 25 °C. This fulfills the target temperature based on the Finnish indoor classification [30] during the occupied hours from 8 to 17 on weekdays.

B. Cooling power demand and the effect of the future climates on room air temperature in cooling design days (1% risk level): The radiant panels' power demand and airflow rates which are designed with the current design day (1% risk level) (Table 7) are simulated with the future cooling design days (1% risk level). The maximum cooling power demands of the two systems for the current and future cooling design days (1% risk level) are presented in Table 8.

At the building level, the maximum total cooling power demand for the all-air system is around 18% higher than the air-water system on the current cooling design day (1% risk level). Additionally, the maximum total cooling power demand at the building level with the air-water system increases by 5.0%, 8.6%, and 13.0% for 2030 RCP4.5, 2050 RCP 4.5, and 2050 RCP 8.5, respectively. For the all-air system, these rises are around 6.7%, 11.5%, and 17.2%, respectively. The maximum cooling power demand at the room level (radiant panels) is almost the same for the current and future design days (1% risk level). This shows that the rises in temperature and enthalpy are handled by the AHU. Thus, the maximum cooling power demand at the AHU level is increasing for the future design days (1% risk level).

For understanding the effects of climate change, the future climate cooling dimensioning cases are simulated with the current climate dimensioning cooling power demand (at the chiller level) (294.1 kW for the air-water system and 348.1 kW for the all-air system). With the limited cooling power, it is important to analyze the condensation risk of the radiant panels since the dehumidification power at AHU is not high enough to cool supply air temperature to the setpoint. Thus to prevent condensation in the rooms, the inlet water temperature of panels is raised according to the supply air temperature for the future scenarios.

Figs. 10 and 11 show the indoor air temperature in the warmest single office (SO2), and the warmest meeting room (MR1), for the current and future cooling design days with limited and unlimited chiller cooling powers. As the figures depict, although the limited cooling capacity of the chiller causes an increase in supply air temperatures, the indoor temperatures are still below the target

Table 5
Different categories of thermal environments based on EN 16798–1.

Type of building or space	Categories	Explanation	Recommended temperature range during the cooling season
Offices and spaces with similar activity (single offices, open-plan offices, conference rooms, auditorium, cafeteria, restaurants, classrooms), activity level ~1.2 met	I	A high level of expectation is only used for spaces occupied by very sensitive and fragile persons	23.5–25.5
	II	Normal expectation for new buildings and renovations	23–26
	III	A moderate expectation (used for existing buildings)	22–27

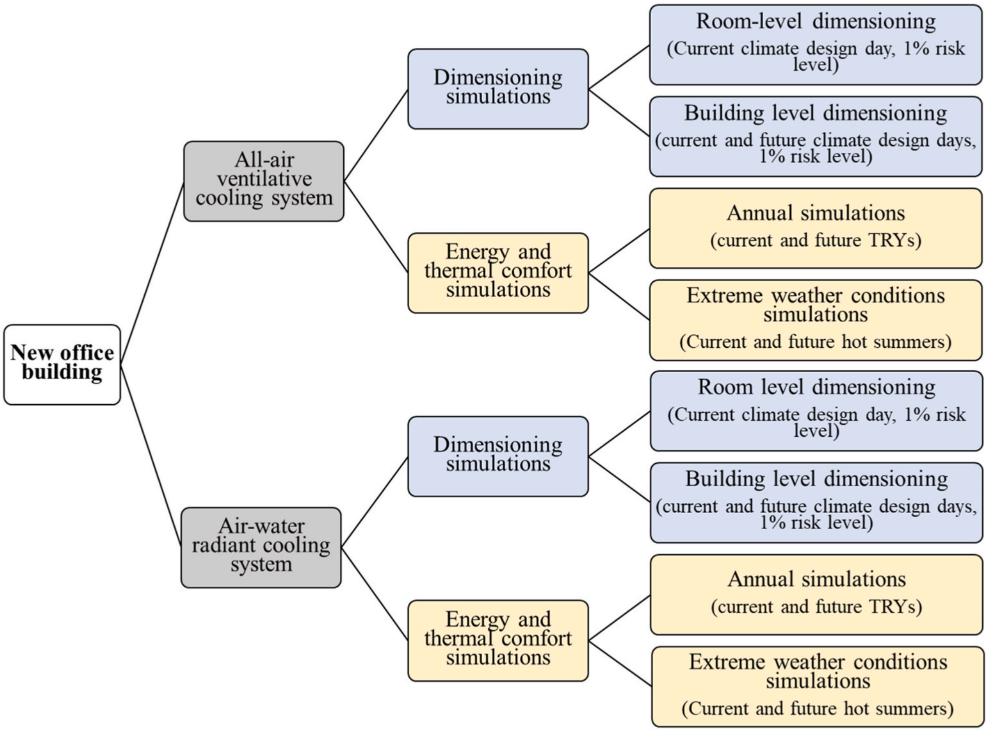

Fig. 9. The process of the simulations.

Table 6
The weather data used in the dimensioning of cooling power and annual simulations of energy demand and thermal comfort.

Cases	System	Weather data
Dimensioning of the cooling powers required	All-air Air-water	**Design cooling days: (July, 1% risk level)** • The current climate • 2030RCP4.5 • 2050RCP4.5 • 2050RCP8.5
Annual energy and thermal comfort analysis	All-air Air-water	**Test reference years:** • TRY2020 • TRY2050 RCP4.5 • TRY2050 RCP8.5 **Extreme weather conditions:** • HS2018 • HS2050 RCP4.5 • HS2050 RCP8.5

Table 7
The sensible cooling power demand for air-water and the required airflow rate of all-air systems with the current cooling design day (1% risk level).

Rooms		Air-water system		All-air system	
		Specific cooling power of radiant panel W/floor m^2	Specific cooling power of ventilation W/floor m^2	Specific cooling power of ventilation W/floor m^2	Specific airflow rates L/s,m^2
Meeting rooms	Lowest power, MR1	10.5	33.3	50.1	min 1 max 4
	Highest power, MR2	34.3	33.7	56.3	
Single office rooms	Lowest power, SO6	12.3	12.9	24.1	min 1 max 2.5
	Highest Power, SO1	31.2	13.1	32.7	

Table 8
The maximum cooling power demand at the building level with the current and future cooling design days (1% risk level).

System			Current climate	2030 RCP 4.5	2050 RCP 4.5	2050 RCP 8.5
Air-water	Radiant panel	kW	51.1	51.5	51.7	52.0
		W/floor m^2	8.9	9.0	9.0	9.1
	AHU	kW	253.9	269.7	281.0	294.8
		W/floor m^2	44.2	46.9	48.9	51.3
	Total cooling power	kW	294.1	308.7	319.4	332.3
		W/floor m^2	51.2	53.7	55.6	57.9
	The difference in total cooling power compared to the current climate design day (%)			5.0	8.6	13.0
All-air	Total (AHU)	kW	348.1	371.5	388.2	408.0
		W/floor m^2	60.6	64.7	67.6	71.0
	The difference in total cooling power compared to the current climate design day (%)			6.7	11.5	17.2

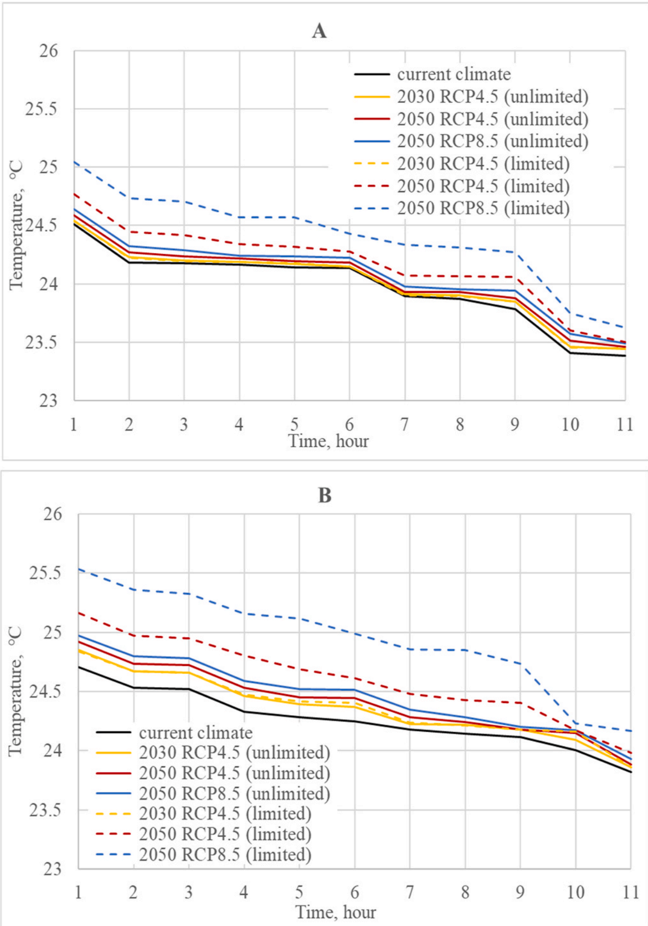

Fig. 10. Duration curves of indoor temperature during the occupied time (8-17) in the warmest single office (SO2) with (A) the air-water system and (B) the all-air system during the cooling design days.

temperature of 25 °C in all spaces with both systems for all the future climate scenarios except for the single office with the all-air system in 2050 RCP4.5 and RCP8.5. Even in these two cases, the maximum temperature is still below 25.5 °C which is the target value of the category I of the EN16798-1. This suggests that designing with the current climate cooling design day, may not cause a problem in terms of indoor air temperature in a changing climate.

3.1.2. Cooling power demand at the building level with average climates and extreme weather conditions

The maximum total cooling power demand at the building level of both systems during the current (TRY2020) and future average (TRY2050) and extreme weather conditions (HS2018 and HS2050) are presented in Table 9. The maximum total cooling power demand is then compared to the current climate dimensioning cooling power demand in this table.

As can be seen, the maximum total cooling power demand at the building level during the current (TRY2020) and future average

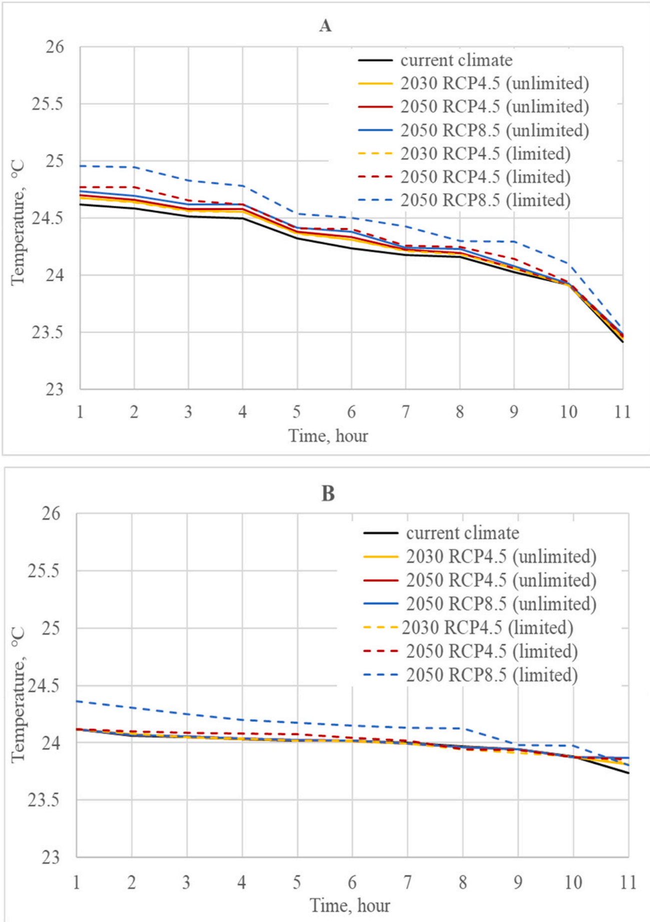

Fig. 11. Duration curves of indoor temperature during the occupied time (8-17) in the warmest meeting room (MR1) with (A) the air-water system and (B) the all-air system during the cooling design days.

climate (TRY2050 RCP4.5/RCP8.5) is below the current climate dimensioning cooling power demand for both systems even if the maximum total cooling power demand in average climate is approaching it in the future. However, the level of the increase due to climate change is higher for the building with the all air system than with the air-water system.

The maximum total cooling power during extreme weather conditions is larger by 16.5%, 27.7%, and 33.5% with the air-water system in HS2018, HS2050 RCP4.5, and RCP8.5, respectively compared to the dimensioning cooling power demand. These numbers are 11.4%, 26.1%, and 33.5% with the all-air system. These rises in the maximum cooling power demand suggest that the current climate dimensioning cooling power demand may not answer the future extreme weather conditions' needs for providing thermal comfort in spaces during the cooling seasons. Thus, the indoor temperature conditions are investigated in section 3.3 during the current and future average and extreme weather conditions with limited chiller cooling power (unlike in Section 3.2 where the cooling power of the chiller is not limited).

3.2. *Energy consumption in current and future climate*

3.2.1. *Annual energy consumption in average climates*

Table 10 shows the purchased energy consumption including district heating of the spaces and ventilation, electricity consumption of space cooling and ventilation, and HVAC auxiliary of the office building under the current average climate (TRY2020) and two scenarios for the future average climate (TRY2050 RCP4.5/RCP8.5).

The total cooling electricity consumption with the air-water system is higher than with the all-air system by 0.6 kWh/m^2 in the current climate. The total electricity consumption with the air-water system is higher than with the all-air system by just 0.2 kWh/m^2 in the current climate. This is because of the lower temperature of the spaces in the air-water system. Compared to the current climate, the cooling electricity increases by 34% and 47% for the building with the air-water system and by 37% and 51% with the all-air system in TRY2050 RCP4.5 and TRY2050 RCP8.5, respectively. On the other hand, the district heating consumption of spaces and ventilation with the air-water system is higher than with the all-air system by 0.7 kWh/m^2 in the current climate. Since the indoor temperature is lower with the air-water system during the mid-season, both cooling and heating systems may be running simultaneously. The district heating consumption of spaces and ventilation decreases by 20% and 27% with the air-water system and by 21%

Table 9
The maximum cooling power demand at the building level during the current cooling design day (1% risk level), the current and future average climates, and extreme weather conditions.

System			Current climate cooling design day	TRY2020	TRY2050 RCP4.5	TRY2050 RCP8.5	HS2018	HS2050 RCP4.5	HS2050 RCP8.5
Air-water	Total cooling power	kW	294.1	283.3	284.2	290.4	342.7	375.6	392.7
		W/floor m^2	51.2	49.3	49.5	50.6	59.7	65.4	68.4
	The difference compared to the current climate design day (%)			−3.7	−3.4	−1.3	16.5	27.7	33.5
All-air	Total cooling power	kW	348.1	270.6	308.5	332.6	387.7	438.9	464.6
		W/floor m^2	60.6	47.1	53.7	57.9	67.5	76.4	80.9
	The difference compared to the current climate design day (%)			−22.3	−11.4	−4.5	11.4	26.1	33.5

Table 10
The purchased energy consumption (kWh/m2) of the office building in the current average climate (TRY2020) and scenarios for the future average climate (TRY2050 RCP4.5 and TRY2050 RCP8.5).

System		TRY2020	TRY2050 RCP4.5	TRY2050 RCP8.5
Air-water	Total cooling elec.[a]	4.7	6.3	6.9
	HVAC aux elec.	7.7	7.7	7.7
	Total elec.	12.4	14.0	14.6
	District heating [b]	29.4	23.4	21.4
	The difference compared to the TRY2020 case (%)			
	Total cooling elec.[a]	–	34	47
	District heating [b]	–	−20	−27
All-air	Cooling elec.	4.1	5.6	6.2
	HVAC aux elec.	8.1	8.3	8.4
	Total elec.	12.2	13.9	14.6
	District heating [b]	28.7	22.8	20.7
	The difference compared to the TRY2020 case (%)			
	Cooling elec.	–	37	51
	District heating [b]	–	−21	−28

[a] Cooling electricity of space and ventilation.
[b] District heat consumption of spaces and ventilation.

and 28% with the all-air system in TRY2050 RCP4.5 and TRY2050 RCP8.5, respectively.

3.2.2. *Cooling energy consumption in extreme weather conditions*

Table 11 shows the total cooling and HVAC auxiliary electricity consumptions during the extreme weather conditions (hot summers) of current and future climate scenarios (HS2018, HS2050 RCP4.5, and HS2050 RCP8.5). These results are calculated for the cases with the unlimited cooling power of the chiller. Since there is no cooling load from October to March, the total annual cooling electricity during extreme weather conditions can be compared with the total cooling electricity for average climates (Table 10). The required cooling electricity under the current climate extreme weather conditions (HS2018) is not only higher than the cooling electricity under the current average climate (TRY2020) by 55.3%, but also it is higher than the cooling electricity under the highest emission scenario case for the future average climate (TRY2050 RCP8.5) in both systems (Table 10). In addition, the cooling electricity of the future extreme weather conditions is higher than in the TRY2020 case by 55–113% for the air-water system and 50–109% for the all-air system depending on the emission scenarios.

3.3. *Indoor temperature conditions*

3.3.1. *Indoor temperature conditions in average climates*

The indoor air temperature during the occupied time on weekdays (8-17) in the warmest single office (SO2), and the warmest meeting room (MR1), in the current and future average climates (TRY2020, TRY2050 RCP4.5, TRY2050 RCP8.5) is shown in Figs. 12 and 13. The degree hours above 24 °C are calculated and presented in Table 12.

The single office is slightly warmer in the cases with the all-air system than with the air-water system during the occupied time of the year (Fig. 12). Instead, although the meeting room with the all-air system is also slightly warmer for almost whole the year, it has lower maximum temperatures than with the air-water system (Fig. 13). This is why the degree hours above 24 °C in the warmest meeting room with the all-air system is the lowest in Table 12 (below 10 Kh even in the highest emission scenario of RCP8.5). Despite the limited cooling power of the chiller, the degree hours above 24 °C is distinctly below 100 Kh in all the scenarios and the indoor air temperature is mostly below the chosen target temperature of 25 °C and within the category I of EN 16798–1 (Table 5). This shows two points: first, both systems can provide almost the same level (category I of EN 16798–1) of thermal comfort in different room types for all the average climate conditions (current and future). Second, the limited cooling power of the chiller and the power needed for dehumidification does not cause a shortage in cooling power and consequently a rise in indoor temperature in future climate scenarios.

Table 11
Electricity consumption (kWh/m2) of the building in extreme weather conditions of the current (HS2018) and future climates (HS2050 RCP4.5 and HS2050 RCP8.5). Comparisons are also shown to the TRY2020 case in Table 9.

System		HS 2018	HS 2050 RCP4.5	HS 2050 RCP8.5
Air-water	Total cooling elec.[a]	7.3	9.2	10
	HVAC aux elec.	4.1	4.1	4.1
	Total elec.	11.4	13.3	14.1
	The difference compared to the TRY2020 case (%)			
	Total cooling elec.[a]	55.3	95.7	112.8
All-air	Cooling elec.	7.0	8.9	9.8
	HVAC aux elec.	4.6	4.9	5.0
	Total elec.	11.6	13.8	14.8
	The difference compared to the TRY2020 case (%)			
	Cooling elec.	48.9	89.4	108.5

[a] Cooling electricity of space and ventilation.

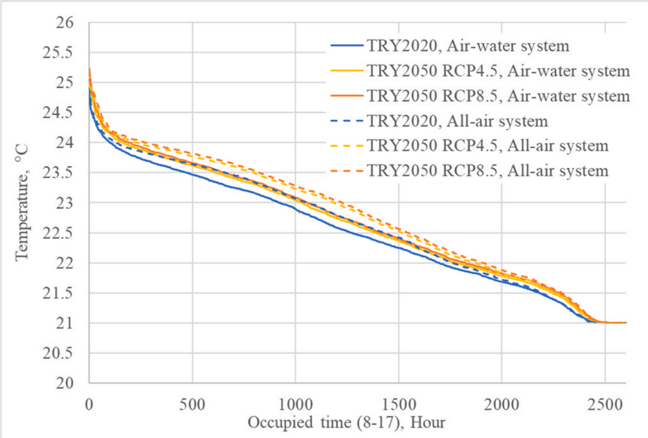

Fig. 12. Duration curve of indoor air temperature in the warmest single office (SO2) in the current and future average climates (TRY2020, TRY2050 RCP4.5, TRY2050 RCP8.5).

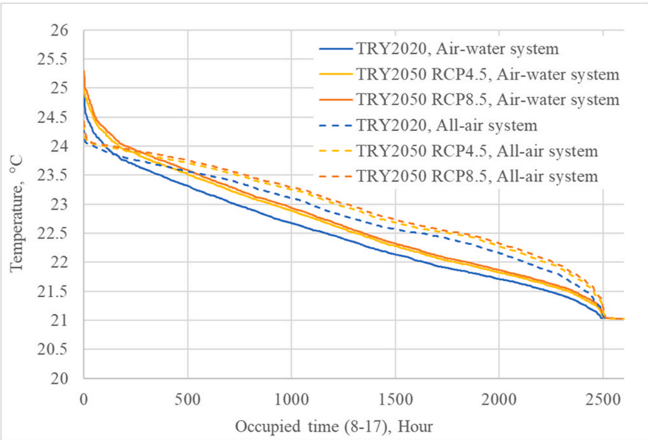

Fig. 13. Duration curve of indoor air temperature in the warmest meeting room (MR1) in the current and future average climates (TRY2020, TRY2050 RCP4.5, TRY2050 RCP8.5).

Table 12
The annual degree hours (Kh) above 24 °C in the warmest single office (SO2) and the warmest meeting room (MR1) in the current and future average climates during the occupied time (8–17 on weekdays.).

	Air-water			All-air		
	TRY2020	TRY2050 RCP4.5	TRY2050 RCP8.5	TRY2020	TRY2050 RCP4.5	TRY2050 RCP8.5
Single office (SO2)	24.5	46.1	56.3	32.0	60.9	74.2
Meeting room (MR1)	27.3	58.1	74.5	2.4	5.7	8.0

3.3.2. Indoor temperature conditions in extreme weather conditions

The indoor air temperature during the occupied time (8–17 on weekdays) from April to September in the warmest single office (SO2), and the warmest meeting room (MR1), in the current and future extreme weather conditions (HS2018, HS2050 RCP4.5, and HS2050 RCP8.5) for both cooling systems are shown in Figs. 14 and 15. These results are for the cases with the dimensioning cooling power of the chiller based on the current climate design day (294.1 kW for the air-water system and 348.1 kW for the all-air system). The degree hours above 24 °C are calculated and presented in Table 13.

The single office is slightly warmer in the cases with the all-air system than with the air-water system during the occupied time, from Apr–Sep (Fig. 14). The meeting room is also slightly warmer for almost the whole occupied time, from Apr–Sep, with the all-air system. However, the maximum temperature of the meeting room is lower with the all-air system than with the air-water system (Fig. 15). This is why the degree hours above 24 °C in the warmest meeting room with the all-air system is the lowest (Table 13). Despite the limited cooling power of the chiller, the indoor air temperature is mostly below the chosen target temperature of 25 °C.

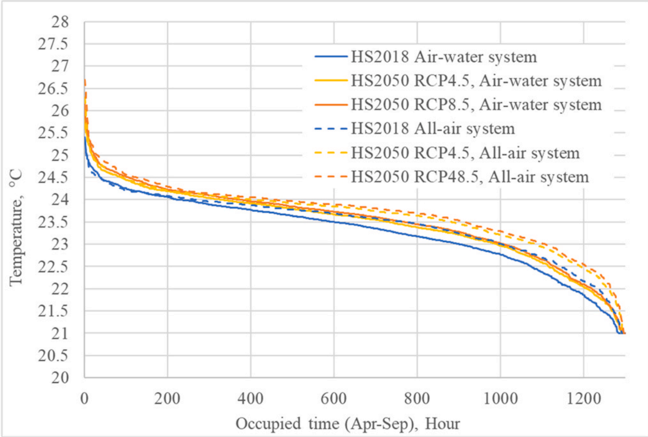

Fig. 14. Duration curve of indoor air temperature in the warmest single office (SO2) in the current and future extreme weather conditions.

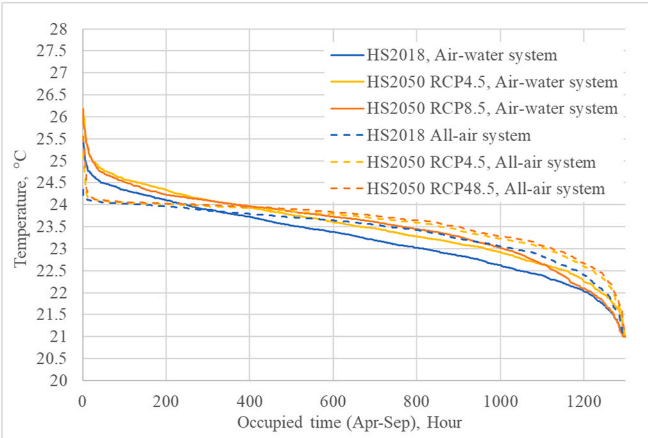

Fig. 15. Duration curve of indoor air temperature in the warmest meeting room (MR1) in the current and future extreme weather conditions.

Table 13
The degree hours (Kh) above 24 °C in the warmest single office (SO2) and the warmest meeting room (MR1) in the current and future extreme weather conditions during the occupied time (8–17 on weekdays) of April–September.

	Air-water			All-air		
	HS2018	HS2050 RCP4.5	HS2050 RCP8.5	HS2018	HS2050 RCP4.5	HS2050 RCP8.5
Single office (SO2)	66.4	116.5	139.9	64.1	132.6	171.6
Meeting room (MR1)	81.1	159.3	139.9	7.3	16.7	25.3

Although the maximum temperature in the highest emission scenario (RCP8.5) for both systems exceeds the chosen target temperature of 25 °C, it is within the category II of EN 16798–1 (Table 5). However, while category I was reached in the average climates (Section 3.3.1), it cannot be reached anymore in extreme weather conditions in the studied cases. This shows that both cooling systems can provide almost the same level (category II of EN 16798–1) of thermal comfort in different room types during future extreme weather conditions.

4. Discussion

The effects of climate change on the HVAC system design and indoor conditions of commercial buildings are not questionable. Since the internal loads in commercial buildings are more or less the same over the world, the outdoor conditions play the main role in cooling systems design. Especially, humidity and enthalpy are important in determining the cooling power of AHU. This is an important issue in choosing cooling systems. All-air (ventilative) and air-water (radiant) cooling systems are different in the breakdown of sensible and latent loads. Room cooling units handle the sensible load and the latent load is carried out by the air-side in the air-water system. The room units can be non-condensing fan coils, chilled beams, radiant cooling panels, etc. Nowadays ceiling radiant cooling panels are commonly used in Finland. On the other hand, both latent and sensible cooling loads are handled by the airflow rates in the all-air system. As the results of this study showed, the specific supply airflow rates with all-air systems are higher than with air-water systems. However, the condensation risk in air-water systems needs to be considered.

The approach of this study is using dynamic simulations to investigate the effects of climate change on the performance of the cooling system. The large simulation campaign has the advantage of comparing the results of a changing parameter through different cases with the same input data. However, the different actual performance of the buildings (the technical and automation issues, etc.) and their occupant's behavior may cause some different results that are hard to be considered in simulations. Since the input data of this study are fixed through all the simulation cases, the results are accurate and comparable.

As shown in the results, for mitigating the effects of climate change on indoor temperature conditions, higher cooling powers are needed. However, dimensioning the cooling systems based on the current climate design day (1% risk level) would be good enough for providing thermal comfort in office spaces. Although the indoor temperature will rise in the scenarios for future average and extreme climates, it will still be in the recommended thermal comfort range. This is an important point since the office buildings are likely to be renovated during their system life span of around 25–30 years and the analyses of this study are done for 2050. Thus, it seems that designing with the current climate design day with 1% risk level is a reasonable choice in the present day.

Climate change is not just about the temperature rise, but as shown, there will be a significant rise in enthalpy. While the enthalpy values even in the future cooling design day under RCP8.5 remain below what was measured in 2010. As reported by Jylhä et al. [39] at several inland locations and an island station, during the prolonged heatwave in 2010, enthalpy was higher than 73 kJ/kg (which is equal to the 1000-year return level estimates derived by Jylhä et al. [40] in 2015. This issue will cause an increase in latent loads and condensation risks. It is an important issue to consider in practice. In this study, the defined outdoor design conditions are assumed to be with 1% risk level. Higher risk levels would cause the system to be undersized considering the effects of climate change and therefore, there would be higher condensations risks. Considering the condensation risks in the system design and changing the inlet water temperature, the airtightness of the envelope, dehumidified supply air below the dewpoint of panel temperature, and enough ventilation to remove internal humidity loads should be considered to control this issue.

In this study, the cooling power demand is assumed to be handled by electricity. However, district cooling and ground-based free cooling are other possible options. District cooling is mostly used in commercial, office, and public buildings as well as top quality apartment blocks which are located in the most built-up parts of cities [54]. Ground source heat pump (GSHP) systems are in use for heating small residential buildings as well as for heating and cooling large commercial and institutional buildings in Finland [55]. Choosing the systems, energy efficiency, cost optimality and sustainability should be considered.

As the results showed, indoor temperature will increase due to climate change during the future average and extreme weather conditions, compared to the current status. These results are conditional to the assumption that system losses, efficiencies, and COP of the cooling systems in the future are the same as now. However, COP of commercial air/water heat pumps rose almost linearly in the 2000s [56]. Improvements in the energy efficiency of cooling systems affect cooling energy, and therefore, indoor temperature conditions. Technical development and advances in building practices are hard to be considered for the future. This should be taken into account when interpreting the quantitative results.

Further uncertainty in the results is related to scenarios for climate change. In this study, we have used a medium and the highest Representative Concentration Pathways (RCP4.5 and RCP8.5) to consider the effects of the global evolution of greenhouse gases and aerosols on future average and extreme climates. Additionally, there are other sources of uncertainty in future projected climatic datasets, arising from internal climate variability, climate modeling, and downscaling methods to develop future hourly weather data sets. In this study, the climate change scenarios for the future are derived from a large sample of climate models [33] which increases confidence in the scenarios in comparison to using just a single model. It may be mentioned that both the RCPs and the climate models utilized in this paper have recently been succeeded by a new set of greenhouse gas scenarios and global climate models; based on the most recent model generation, warming is fairly similar in winter but stronger in summer compared to the climate projections used in this paper [57].

Regarding the hot summer of 2018 in Finland, a real past high-impact climatic event, our approach was to assess how it might unfold in the future due to the changing climate (Section 2.2.3) and then to demonstrate how its impacts (Sections 3.2.2 and 3.3.2) might differ from the past in such recurring hot weather conditions. This approach may be regarded as a step toward so-called physical climate storylines (e.g. Ref. [58]) or event-based storylines [59]. Such storylines, built on past incidents and combined with climate change information, have recently emerged as an alternative way to address plausible high-impact events and to provide actionable information on the predicted future.

5. Conclusions

The impacts of climate change on dimensioning of two different cooling systems including all-air (ventilative cooling) and air-water (radiant cooling) are assessed using the new cooling design days (1% risk level) for southern Finland, in an office building. Additionally, the effects of climate change and associated hot summers on the maximum cooling power demand, cooling energy consumption, and indoor temperature conditions are analyzed. The new cooling design days of current and future climate of southern Finland with 1% risk level, TRY2020, and TRY2050 under the RCP4.5 and RCP8.5, actual weather data of hot summer 2018, and synthetic future weather data of hot summer 2050 under the RCP4.5 and RCP8.5 are used as the input of IDA ICE simulations.

According to the results, the dimensioning cooling power increases significantly for both cooling systems using the future climate design days compared to the current climate design day. However, the cooling system dimensioned using the current climate design day with 1% risk level can keep the indoor temperature within the thermal comfort recommended range. As the indoor temperature in the warmest meeting room and single office room meets the criteria recommended by category I of the EN 16798-1 standard during the current and future average climate. Nonetheless, during the current and future extreme weather conditions, the indoor temperature conditions will exceed the target temperature of 25 °C if the cooling system is designed with the current climate design day with 1% risk level. However, it will still be within the category Π of the EN 16798-1 standard.

Comparing the chosen cooling systems, the current climate dimensioning cooling power for the all-air system is 18% higher than for the air-water system with the current climate cooling design day. With future climate design days, the maximum total cooling power demand will increase up to 13% with the air-water system and 17% with the all-air system by 2050 depending on CO_2 emission scenarios.

Considering the annual simulations' results, the maximum total cooling power demand during the test reference years in the current (TRY2020) and future (TRY2050) average climates is smaller than the current climate dimensioning cooling power in both systems. While the maximum total cooling power demand in the current and future extreme weather conditions (2018 and 2050) is significantly higher than the current climate dimensioning cooling power in both systems. It is worth mentioning that climate change mainly increases the cooling power demand of ventilation and the cooling power demand of room units stays quite similar in the future. This shows that the rises in temperature and enthalpy are mostly covered by the AHU in the future.

According to the results of energy consumption with the assumption of the same system efficiency now and in the future, the total cooling electricity consumption is higher in the air-water (radiant) system than in the all-air (ventilative) system in all the current and future average and extreme weather conditions. Nevertheless, the total electricity consumption of both systems considering the HVAC auxiliary electricity is mostly at the same level in the current and future average climates. The cooling electricity will increase up to 47% in the future average climate and up to 128% in the future extreme climate with the air-water system, and up to 51% in the future average climate and 108% in the future extreme climate with the all-air system by 2050 depending on CO_2 emission scenario. Thus, the magnitude of increase in the cooling electricity in future average and extreme climates are relatively the same for both systems.

These findings suggest that in general the two studied cooling systems, (ventilative and radiant) equally perform in terms of cooling energy consumption and indoor temperature conditions under a changing climate. However, it is worth mentioning that the maximum cooling power demand would be higher with the all-air system (ventilative) during extreme weather conditions.

The contribution of this study has been to confirm the severity of climate change issues and their effects on the HVAC systems design and configuration. This research has thrown up many questions in need of further investigation. More detailed analyses are recommended for the increase in outdoor enthalpy due to climate change and its effect on the cooling systems performance, condensation risks with air-water systems, and indoor thermal conditions in mechanically cooled buildings of any type in different climates. Moreover, the effects of different control strategies on mitigating the climate change effects can be investigated in the cold climate.

Author contributions

Conceptualization: A.V., R.K., and J.J. Data Curation: A.V. Formal Analysis: A.V. Methodology: A.V., N.K. S.L. Investigation: A.V. Supervision: R.K. Writing—Original Draft: A.V., N.K. Writing—Review and Editing: R.K., J.J., K.J., and K.R. S.L. All authors have read and agreed to the published version of the manuscript.

Funding

This study is part of the following projects: HEATCLIM (Heat and health in the changing climate, Grant Numbers. 329306, 329307) funded by the Academy of Finland within the CLIHE (Climate change and health) program, FINEST Twins funded by the European Union (Horizon 2020 program, Grant No. 856602), and the Estonian government, SUREFIT (Sustainable solutions for affordable retrofit of domestic buildings) funded by European Union (Horizon 2020 program, Grant No. 894511). and ACCC (Atmosphere and Climate Competence Center) funded by the Academy of Finland (Flagship Grant No. 337552).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Jouko Niemelä and Mika Vuolle from EQUA Simulation Finland Ltd. for defining an office building model in the Cost Optimal project. Weather observational data archived by the Finnish Meteorological Institute and CMIP5 global climate model data archived by the Earth System Grid Federation (https://esgf-node.llnl.gov/search/cmip5/accessed date April 26, 2021) were used in this study. Kimmo Ruosteenoja, Herman Böök, Anders Lindfors, and Pentti Pirinen are acknowledged for the provision and post-processing of the data.

References

[1] IPCC 2021 V. Masson-Delmotte, P. Zhai, Y. Chen, L. Goldfarb, M.I. Gomis, J.B.R. Matthews, et al., Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Internet, 2021. Available from: www.ipcc.ch.

[2] D. Coumou, S. Rahmstorf, A decade of weather extremes, Nat. Clim. Change 2 (2012) 491–496.

[3] A. Rutgersson, E. Kjellström, J. Haapala, M. Stendel, I. Danilovich, M. Drews, et al., Natural hazards and extreme events in the Baltic Sea region, Earth Syst. Dynam. 13 (1) (2022 Feb 2) 251–301.
[4] V. Kollanus, P. Tiittanen, T. Lanki, Mortality risk related to heatwaves in Finland – factors affecting vulnerability, Environ. Res. 201 (2021 Oct), 111503.
[5] A. Jiang, Y. Zhu, A. Elsafty, M. Tumeo, Effects of global climate change on building energy consumption and its implications in Florida, Int. J. Construct. Educ. Res. 14 (1) (2018) 22–45.
[6] E. Recast, Implementing Article 11(1) of Regulation (EU), Official Journal of the European Union, 2018. Council Implementing Regulation (EU) 2018/31 of 10 January 2018.
[7] P. Bertoldi, J. Kihila, A.F.P. Lucena, É. Mata, S. Mirasgedis, A. Novikova, et al., Mitigation of Climate Change Climate Change 2022 (Chapter 9): Buildings [Internet, 2022. Available from: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.
[8] M. Cellura, F. Guarino, S. Longo, G. Tumminia, Climate change and the building sector: modelling and energy implications to an office building in southern Europe, Energy Sustain. Dev. 45 (2018 Aug 1) 46–65.
[9] A.T. Nguyen, D. Rockwood, M.K. Doan, T.K. Dung Le, Performance assessment of contemporary energy-optimized office buildings under the impact of climate change, J. Build. Eng. 35 (2021 Mar 1), 102089.
[10] U. Berardi, P. Jafarpur, Assessing the impact of climate change on building heating and cooling energy demand in Canada, Renew. Sustain. Energy Rev. 121 (2020 Apr 1), 109681.
[11] M. Li, J. Cao, M. Xiong, J. Li, X. Feng, F. Meng, Different responses of cooling energy consumption in office buildings to climatic change in major climate zones of China, Energy Build. 173 (2018 Aug 15) 38–44.
[12] D.H.W. Li, S.L. Wong, J.C. Lam, Climatic effects on cooling load determination in subtropical regions, Energy Convers. Manag. 44 (2003) 1831–1843.
[13] M.A. Aktacir, O. Büyükalaca, H. Bulut, T. Yilmaz, Influence of different outdoor design conditions on design cooling load and design capacities of air conditioning equipments, Energy Convers. Manag. 49 (6) (2008) 1766–1773. Jun.
[14] American Society of Heating, Refrigerating and Air-Conditioning Engineers. ANSI/ASHRAE Standard 169-2013: Climatic Data for Building Design Standards, NYC, USA, 2021.
[15] X. Xu, Z. Tian, K. Liu, M. Li, J. Guo, F. Liang, The optimal period of record for air-conditioning outdoor design conditions, Energy Build. 72 (2014 Apr) 322–328.
[16] L. Kajtar, S. Vörös, Influence of climate change on modelling of HVAC systems, in: EE'07: Proceedings of the 2nd IASME/WSEAS International Conference on Energy and Environment, 2007, pp. 232–235.
[17] T. Chen, Z. Yu, A statistical method for selection of sequences of coincident weather parameters for design cooling load calculations, Energy Convers. Manag. 50 (3) (2009 Mar) 813–821.
[18] F.W. Yu, K.T. Chan, R.K.Y. Sit, Climatic influence on the design and operation of chiller systems serving office buildings in a subtropical climate, Energy Build. 55 (2012 Dec 1) 500–507.
[19] Y.H. Yau, S. Hasbi, A comprehensive case study of climate change impacts on the cooling load in an air-conditioned office building in Malaysia, in: Energy Procedia, Elsevier Ltd, 2017, pp. 295–300.
[20] D. Sánchez-García, C. Rubio-Bellido, J.J.M. del Río, A. Pérez-Fargallo, Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change, Energy Build. 187 (2019 Mar 15) 173–185.
[21] P. Jafarpur, U. Berardi, Effects of climate changes on building energy demand and thermal comfort in Canadian office buildings adopting different temperature setpoints, J. Build. Eng. 42 (2021 Oct 1), 102725.
[22] L. Wang, X. Liu, H. Brown, Prediction of the impacts of climate change on energy consumption for a medium-size office building with two climate models, Energy Build. 157 (2017 Dec 15) 218–226.
[23] K.K.W. Wan, D.H.W. Li, J.C. Lam, Assessment of climate change impact on building energy use and mitigation measures in subtropical climates, Energy 36 (3) (2011 Mar 1) 1404–1414.
[24] Y. Khan, V.R. Khare, J. Mathur, M. Bhandari, Performance evaluation of radiant cooling system integrated with air system under different operational strategies, Energy Build. 97 (2015 Jun 15) 118–128.
[25] H. Pieskä, A. Ploskić, Q. Wang, Design requirements for condensation-free operation of high-temperature cooling systems in mediterranean climate, Build. Environ. 1 (2020 Nov) 185.
[26] D.O. Rijksen, C.J. Wisse, A.W.M. van Schijndel, Reducing peak requirements for cooling by using thermally activated building systems, Energy Build. 42 (3) (2010 Mar) 298–304.
[27] B. Ning, Y. Chen, H. Jia, Cooling load dynamics and simplified calculation method for radiant ceiling panel and dedicated outdoor air system, Energy Build. 15 (2020 Jan) 207.
[28] T. Vainio, T. Vesanen, A. Laitinen, M. Haakana, P. Kalliomäki, Calculation of Cost-Optimal Levels of Minimum Energy Performance Requirements in New Construction Projects, 2018 [Internet]. Report to the European Commission under Article 5(2) of the Energy Performance of Buildings Directive (2010/31/EU) for mainland Finland: https://energy.ec.europa.eu/eu-countries-2018-cost-optimal-reports_en [cited 2022 Feb 23]. Available from.
[29] Ministry of social affairs and health, Decree (525/2015) on Housing Health. (Sosiaali- Ja Terveysministeriön Asetus Asunnon Ja Muun Oleskelutilan Terveydellisistä Olosuhteista Sekä Ulkopuolisten Asiantuntijoiden Pätevyysvaatimuksista), vol. 2, 2015, p. 6. Helsinki, Finland.
[30] Standard SFS-EN 16798-1. Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, Finnish Standards Association SFS, Helsinki, Finland, 2019.
[31] Finnish Society of Indoor Air Quality and Climate, Finnish IEQ classification, 2018, pp. 1–24. M.
[32] A. Velashjerdi Farahani, J. Jokisalo, N. Korhonen, K. Jylhä, K. Ruosteenoja, R. Kosonen, Overheating risk and energy demand of nordic old and new apartment buildings during average and extreme weather conditions under a changing climate, Appl. Sci. 11 (9) (2021 Apr 27) 3972.
[33] K. Ruosteenoja, K. Jylhä, M. Kämäräinen, Climate projections for Finland under the RCP forcing scenarios, Geophysica 51 (1–2) (2016) 17–50.
[34] D.P. van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, et al., The representative concentration pathways: an overview, Climatic Change 109 (1) (2011) 5–31.
[35] O. Saranko, C. Fortelius, K. Jylhä, K. Ruosteenoja, E. Brattich, S. di Sabatino, et al., Impacts of town characteristics on the changing urban climate in Vantaa, Sci. Total Environ. 727 (2020), 138471. Jul.
[36] K. Jylha, K. Ruosteenoja, H. Book, A. Lindfors, P. Pirinen, M. Laapas, et al., Weather Data for Building-Physical Studies and the Building Energy Reference Year 2020 in a Changing Climate, Finnish Meteorological Institute, 2020, p. 81. Reports 20((In Finnish with abstract in English)).
[37] K. Jylhä, K. Ruosteenoja, J. Jokisalo, K. Pilli-Sihvola, T. Kalamees, H. Mäkelä, et al., Hourly test reference weather data in the changing climate of Finland for building energy simulations, Data Brief 4 (2015) 162–169. Sep.
[38] EN ISO 15927-2 European Committee for Standardization, Hygrothermal Performance of Buildings—Calculation and Presentation of Climatic Data—Part 2: Hourly Data for Design Cooling Load, 2009. Brussels, Belgium.
[39] K. Jylhä, M. Kämäräinen, C. Fortelius, H. Gregow, J. Helander, O. Hyvärinen, et al., Recent meteorological and marine studies to support nuclear power plant safety in Finland, Energy 165 (2018 Dec) 1102–1118.
[40] [InternetK. Jylhä, S. Saku, A. Venäläinen, J.S.V. Hämäläinen (Eds.), High Specific Enthalpy in the Recent and Projected Future Climate of Finland, 2015 [cited 2022 Mar 8]. Available from: 08/03/2022, https://www.vttresearch.com/sites/default/files/pdf/technology/2015/T213.pdf.
[41] T. Kalamees, K. Jylhä, H. Tietäväinen, J. Jokisalo, S. Ilomets, R. Hyvönen, et al., Development of weighting factors for climate variables for selecting the energy reference year according to the en ISO 15927-4 standard, vol. 47, Energy and Buildings, 2012, pp. 53–60, https://doi.org/10.1016/j.enbuild.2011.11.031 [Internet], Available from:.
[42] Finnish Meteorological Institute (FMI), Heat Statistics (In Finnish), 2021. https://www.ilmatieteenlaitos.fi/helletilastot.
[43] J. Sillmann, E. Roeckner, Indices for extreme events in projections of anthropogenic climate change, Climatic Change 86 (1–2) (2008 Jan 4) 83–104.
[44] V.A. Sinclair, J. Mikkola, M. Rantanen, J. Räisänen, The summer 2018 heatwave in Finland, Weather 74 (11) (2019 Nov 19) 403–409.

[45] Finnish Institute for Health and Welfare (THL), Last Summer's Heat Wave Increased the Mortality of Older People – Prepare for Hot Weather in Time [Internet], 2019 cited 2021 Feb 16]. Available from: https://thl.fi/en/web/thlfi-en/-/last-summer-s-heat-wave-increased-the-mortality-of-older-people-prepare-for-hot-weather-in-time.
[46] R. Ruuhela, A. Votsis, J. Kukkonen, K. Jylhä, S. Kankaanpää, A. Perrels, Temperature-related mortality in Helsinki compared to its surrounding region over two decades, with special emphasis on intensive heatwaves, Atmosphere 12 (1) (2020 Dec 30) 46.
[47] FMI, Warm Temperature Records Broken in July [Internet], FMI Press Release Archive, 2018. cited 2021 Feb 17]. Available from: https://en.ilmatieteenlaitos.fi/press-release/610918514.
[48] P. Sahlin, Modeling and Simulation Methods for Modular Continuous Systems in Buildings, vol. 39, Department of Building Sciences, Division of Building Services, 1996.
[49] S. Moinard, G. Guyon, Empirical Validation of EDF ETNA and GENEC Test-Cell Models, 2000.
[50] J. Travesi, G. Maxwell, C. Klaassen, M. Holtz, Empirical Validation of Iowa Energy Resource Station Building Energy Analysis Simulation Models, 2001.
[51] P. Loutzenhiser, H. Manz, IEA Task 34 - Testing of Building Energy Simulation Tools Project -, 2014.
[52] A.B. Equa Simulation, Validation of IDA Indoor Climate and Energy 4.0 with Respect to CEN Standards [Internet], 2010 [cited 2022 May 13]. Available from: http://www.equaonline.com/iceuser/validation/CEN_VALIDATION_EN_15255_AND_15265.pdf.
[53] Kropf S, Zweifel G. Validation of the Building Simulation Program IDA-ICE According to CEN 13791 "Thermal Performance of Buildings-Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling-General Criteria and Validation Procedures" [Internet]. [cited 2022 May 13]. Available from: http://www.equaonline.com/iceuser/validation/ICE_vs_prEN%2013791.pdf.
[54] T. Vainio, T. Lindroos, E. Pursiheimo, T. Vesanen, K. Sipilä, M. Airaksinen, et al., High-efficiency CHP, District Heating and District Cooling in Finland, 2010.
[55] J.-E. Nowacki, Heat Pumps in Energy Statistics – Suggestions, Lidingö, Sweden, 2007.
[56] M. Tono, Country report Japan, in: 9th International IEA Heat Pump Conference, The 9th International IEA heat pump conference, Zürich, Switzerland, 2008, pp. 20–22. May.
[57] K. Ruosteenoja, K. Jylhä, Projected Climate Change in Finland during the 21 St Century Calculated from CMIP6 Model Simulations, vol. 56, 2021.
[58] N. Schaller, J. Sillmann, M. Müller, R. Haarsma, W. Hazeleger, T.J. Hegdahl, et al., The role of spatial and temporal model resolution in a flood event storyline approach in western Norway, Weather Clim. Extrem. 29 (2020 Sep), 100259.
[59] J. Sillmann, T.G. Shepherd, B. van den Hurk, W. Hazeleger, O. Martius, J. Slingo, et al., Event-based storylines to address climate risk, Earth's Future 9 (2) (2021 Feb 17).