Comparative Analysis of Air-Based and Water-Based Cooling Systems in Office Buildings Under Changing Climate and Extreme Weather Conditions

---

Mingyin Xu

Master thesis in Energy-efficient and Environmental Buildings

Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Kavan Javanroodi (Division of Building Physics)

Supervisor: Vahid Nik (Division of Building Physics), Taha Arghand (Bengt Dahlgren)

Keywords: Variable air volume system, Ceiling radiant cooling panels system, energy performance, life cycle cost, future climate

Publication year: 2024

Abstract

As climate change continues leads to rising global temperatures and poses the threat of extreme weather conditions, the cooling energy demand within the building sector is experiencing rapid growth. This study aims to compare both energy performance and cost efficiency between all-air cooling systems and water-based cooling systems by investigating variable air volume (VAV) system and ceiling radiant cooling panel (CRCP) system in a nine-storey office building located in Gothenburg, Sweden.

To conduct these comparisons, the professional energy simulation software IDA-ICE was employed to dimension the system size and energy simulations for both systems. The analysis encompassed energy demands for heating, cooling and HVAC auxiliary electricity. In addition, life cycle costs, including investment, maintenance and operational costs, were calculated to identify the most cost-effective mechanical cooling system over a long term (20 years). Furthermore, the study evaluated thermal comfort for each cooling system under both current and future climate scenarios.

The findings indicate that although the VAV system consumes less total energy as utilizing free cooling, it requires higher peak power compared to the CRCP system. Conversely, the CRCP system shows significant potential for reducing peak power demand and HVAC auxiliary electricity due to low airflow, thereby leading to long-term cost savings. The parametric analysis on external and internal loads shows that in winter, high external loads cause CRCP system consuming more energy for heating with high constant airflow, while high internal loads cause the VAV system consuming more energy for heating due to need of cooling for center zones. Moreover, the CRCP system can improve thermal comfort level for the occupants because it can provide lower and more table operative temperatures compared to the traditional VAV system. The initial investment of the CRCP system is slightly higher than that for VAV system, but it requires lower maintenance cost compared to VAV system. Over a 20-year calculation period, the CRCP system achieves a lower LCC. Despite having slightly higher annual energy costs than the VAV system in future climate scenarios, the overall cost efficiency of the CRCP system remains superior.

In conclusion, the CRCP system represents a viable and cost-effective alternative to traditional VAV systems, both under current and future climate scenarios, except under super high external loads condition.

Acknowledgements

This research gained from the project "How prepared are Swedish detached houses to adapt to Climate Change?" (2021-02389) funded by the Swedish research council for sustainable development (FORMAS). Financial support from the Swedish Construction Industry Development Fund (SBUF) for the project “Jämförande analys av luftburna och vattenburna kylsystem i kontorsbyggnader” is greatly appreciated.

I would like to express my sincere gratitude to Taha Arghand from Bengt Dahlgren for granting me the opportunity to undertake my master’s thesis in collaboration with them. His assistance with the simulation software IDA-ICE and his valuable guidance and feedback helped me to navigate the challenges of this project.

I also express my appreciation to my supervisor, Vahid Nik from the Division of Building Physics, Faculty of Engineering, Lund University, for his support and insightful suggestions throughout the thesis process. His expertise and assistance in researching under future climate conditions were invaluable.

I am deeply grateful to my parents for their unwavering support, allowing me to study abroad at Lund University. I also want to thank myself for embracing and enjoying these two years in Sweden and for experiencing the rich European culture.

Lastly, I express my gratitude to all the professors and classmates for making these two years a joyful experience.

Mingyin Xu

Lund, June 2024

Contents

List of Acronyms

CAV	Constant Air Volume
VAV	Variable Air Volume
AHU	Air Handling Unit
CRCP	Ceiling Radiant Cooling Panels
LCC	Life Cycle Costs
NPV	Net Present Value
COP	Coefficient of Performance

List of Figures

List of Tables

1 Introduction

This chapter starts with the background of the study, introducing the theories of air-based and water-based mechanical cooling systems, as well as a review of current studies in this area. In the following, an overview of the purpose, research questions, scope and limitations are provided.

1.1 Background

The building sector stands as a substantial contributor to the global energy landscape, accounting for about 36% of energy consumption [1]. This consumption is mainly attributed to the operation of heating, ventilation, and air conditioning (HVAC) systems [2], which play a pivotal role in maintaining thermal comfort of the rooms across diverse climates and seasons. Furthermore, escalating carbon dioxide emissions is a primary threat to global climate change and urban overheating, where the building sector is responsible for about 39% of the process related to carbon dioxide emissions [3].

Global space cooling demand is continuing rising in the context of climate change. It is the fastest growing of energy demand of the building sector and it is estimated that the future cooling energy consumption may rise by 200% and up to 2000% by 2050 [4]. Moreover, with around 60% of cooled floor area in Europe, commercial buildings such as offices demonstrate the cooling demand that is twice as high as that of residential buildings, emphasizing the significant influence of commercial buildings on energy consumption and cooling requirements [5].

Under this background, this research focuses on the energy saving potential of the mechanical cooling systems. The following section introduces the principles of various mechanical systems and provides a summary of current literature regarding their performance.

1.1.1 Cooling systems

All-air ventilation systems, encompassing constant air volume (CAV), variable air volume (VAV), and demand control ventilation (DCV) approaches, constitute the most prevalent cooling methods for commercial buildings in Sweden. These systems rely only on air to remove heat from the spaces by convection in the building. Among these three approaches, VAV system is the most predominant space cooling system in office buildings today. It distributes conditioned outdoor air to the building through a central air handling unit (AHU) via fans and ductwork. Meanwhile, each terminal has a controller which can regulate the supplied air volume at specific temperatures to achieve and uphold zone thermal comfort for various occupancy rates and cooling loads [6]. Figure 1 presents a typical VAV system that consists of an AHU and VAV boxes, typically with one VAV box per zone [7]. The principle of VAV systems is by opening or closing mechanical dampers to modulate airflow to satisfy each zone's temperature setpoints. The outdoor air temperature of Sweden is generally resting below room temperature for a significant portion of the year. Therefore, VAV system enables utilization of free cooling from the outdoor environment to achieve energy efficiency.

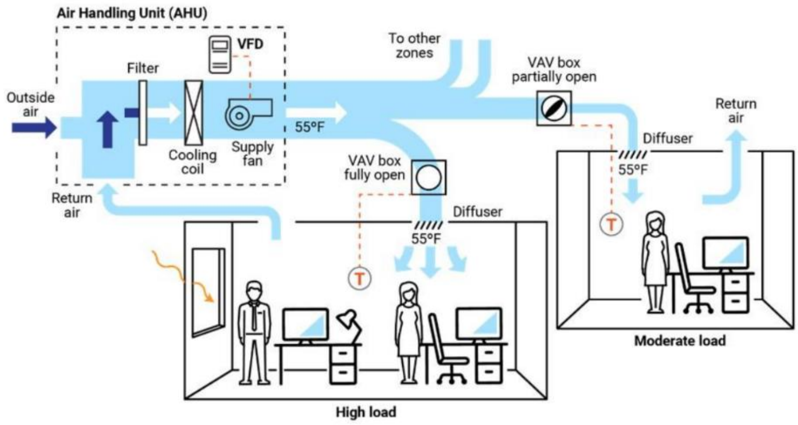


Figure 1 A typical VAV system. Source: "Variable Air Volume (VAV) Systems Operations and Maintenance." Available: https://www.pnnl.gov/projects/om-best-practices/variable-air-volume-systems [7].

Water-based radiant cooling systems can be used as viable alternatives to the all-air systems in office buildings. These systems rely mainly on water as the cooling medium for thermal conditioning of the spaces and most of heat will be removed by radiation. Since most of heat can be removed by water, the role of supply air primarily serves to uphold indoor air quality, which results in notable reduction of the energy consumption of fans due to the decreased airflow rate [8]. However, these systems can only remove the sensible load from a space and must be combined with an air ventilation system for removing latent loads through dehumidification [9].

A typical water-based radiant cooling system uses ceiling cooling panels, which are built as an architectural finish product and compatible with the traditional drop ceiling "Tee grid" system, or as a free hanging element. Cold water circulates through the aluminum multi-layer composite pipe and cools the entire surface of the ceiling [10]. Compared with all-air systems that depend on convection only, ceiling radiant cooling panels (CRCP) system provides cooling by a combination of radiation and convection [11]. Aluminum panel and cooling water piping consist ceiling radiant cooling panels and panel piping arrangements are generally in a serpentine pattern [10]. Figure 2 illustrates the typical panel construction and its installation.

Sensible heat is removed from space by a combination of convection and radiation. In most applications, the heat removed by each of the two mechanisms is roughly equal, and governed by the difference between the panel mean temperature and the enclosure mean temperature [10]. However, because of the potential for condensation, a parallel system must be installed in place to decouple the space sensible and latent loads, as a results, dedicated outdoor air system (DOAS) is recommended to remove space latent heat [9], [12]. Since the role of supply air primarily serves of hygienic reason and dehumidification, it can significantly decrease the draught risks by reducing the vertical drop of an air jet, which is often observed in all-air system, as well as provide an ideal vertical air temperature gradient and mitigate cold draught due to excessive air movement.

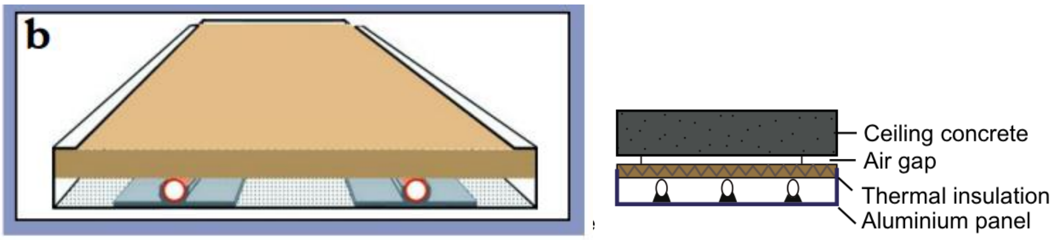


Figure 2 Typical ceiling panel construction: panel with back insulation and acoustical perforation. Source: S. A. Mumma, "Ceiling Panel Cooling Systems," ASHRAE Journal, 2001 [10].

Moreover, CRCP systems can provide the equivalent thermal comfort at a higher air temperature and thus have energy-saving potential. Due to the small temperature differences between the cooled surface and occupied space, it can benefit from the self-regulating effect, which can provide a stable thermal environment for the occupants within the space [11].

The cooling capacity of CRCP varies with temperature differences between mean water and air linearly. The performance curve always can be provided by the manufacturer with different types and installations.

Although both air-based (by convection) and water-based (by radiation and convection) cooling technologies can provide acceptable thermal indoor environment, they differ from each other in energy use and operational costs, investment costs, required space for ducts, etc. These differences will likely be even more distinct considering the effects of heatwaves in the changing climate. Consequently, it is essential to study and compare the energy consumption and peak power needs of two different cooling systems.

1.1.2 Literature review

According to the current literature, the ceiling radiant cooling panels system, which is a water-based radiant cooling system, is a feasible alternative to VAV systems. CRCP systems are believed to be energy efficient and economical. The current literature confirms that the reduced airflow rate enables the use of smaller AHUs and ductwork, resulting in more efficient and cost-effective designs. Miriel et al. [13] did an experiment in France and found the power of CRCP system was limited and the cooling loads was lower with similar indoor air temperature. A comparison between CRCP system and convectional all-air system has been done under climate conditions of Copenhagen, Denmark, finding that the radiant system reduced peak loads, resulting in 20% reduction in peak power demand compared to the conventional all-air system

[14]. Another study demonstrated that the total energy use of radiant system was 10% lower than the all-air system, with approximately 10% cost savings as well [15]. Likewise, 78% of fan energy could be saved in a hot-humid climate compared to constant air ventilation system [2].

However, when designing CRCP systems for cooling, condensation mitigation has to be taken into consideration. Many studies have extensively investigated condensation control [16], offering valuable guidelines and design techniques aimed at improving convection and radiation performance while effectively eliminating condensation [17-19].

Furthermore, CRCP systems offer advantages to the thermal comfort of the buildings. Liao et al. conducted an experiment comparing two testing rooms: one equipped with an all-air cooling system while the other with CRCP. Their findings revealed that the temperature fluctuations in the CRCP room were notably reduced compared to the room with conventional air cooling. Specifically, the vertical temperature gradient in the CRCP room was only 27.5% of that in the air-cooled room, and the horizontal temperature fluctuation was just one-third of the air-cooled room [20].

Overall, a limited number of studies have explored the energy performances of CRCP systems in comparison to VAV systems. Additionally, while CRCP systems have been adopted in countries such as Denmark and Germany, which share similar climate characteristics with Sweden, their application has not been extensively investigated in Sweden, especially in terms of overall energy efficiency, life-cycle costs, and future climate impact.

1.2 Purpose and aim

The purpose of this work is to achieve both energy-efficient and cost-effective design for cooling systems in office buildings through a better understanding of the design and operation of mechanical cooling systems, especially VAV system and ceiling cooling panel system. In doing so, both current and the future climate challenges are taken into consideration. The differences in energy consumption, peak power demand and life-cycle costs will be investigated based on comparisons.

The specific aim of this work is to investigate ceiling cooling panel system as one of the alternatives for two office buildings in Sweden and to conduct a particular comparison between VAV and ceiling cooling panel systems in office buildings considering climate change and its associated heatwaves for the Swedish climate. The comparison includes analysis of purchased energy use, peak power demand, investment costs for the cooling systems, annual energy costs, and thermal comfort in office spaces.

Additionally, ceiling cooling panels are used in other countries with relatively similar climate characteristics as Sweden such as Denmark and Germany, but its application has not been extensively investigated in Sweden. This will be the first study on this system in Sweden. This aspect, in particular, links this study to the industrial partners of this project.

1.3 Research questions

The following four research questions have been discussed to achieve the purpose and aims of this project:

1) What are the purchased energy and peak power demand differences between VAV system and CRCP system?

2) What are the life cycle cost differences between VAV system and CRCP system?

3) How do internal loads and external loads affect the energy performances of the building?

4) What will be the energy performance of the building under projected future climate?

1.4 Scope and limitations

This work was established based on the specific case building. The building's geometry, constructions, orientation, occupancy and other use schedules all affect the design of systems and energy performances. Therefore, the results given and compared in this work only provide a reference of results for buildings with similar characteristics. Likewise, the study is bound to oceanic climate (Cfb according to the Köppen climate classification) [21] as the case buildings are located in Gothenburg, Sweden. Furthermore, the future energy performance was also evaluated based on projected future climate in Sweden simulated by regional climate models.

The study is a simulation study without any practical measurement. Additionally, the panels can only set to a rectangular shape and cannot be rotated, making it challenging to accurately cover the ceiling area in some zones, resulting in inaccurate count and area of panels. Consequently, the results can only be reliably applied for comparative assessment of performance rather than the determination of the absolute system performances of the buildings.

The work does not concern the details and specific design of VAV. Detailed engineering aspects, such as the layout and component selection are beyond the scope of this work.

Regarding life-cycle costs analysis, the investment costs are estimated based on experience values, where the costs per floor area, provided by the cooperated company, were used. As a result, the investment costs for VAV systems and CRCP systems remain constant regardless of changes of the building demands. This means that there is a gap between the projected results and the actual situation.

2 Methodology

This section starts with a short description about simulation software used in this work. Afterwards the studied case building and its usage profile are presented briefly. In the following the methodology of the study is described systematically, covering simulation resources, system designs, thermal comfort analysis and life cycle costs calculations.

2.1 Simulation software

This study was based on building energy simulation, using the professional energy simulation software IDA indoor climate and energy (IDA-ICE) version 4.8 SP2 [22].

The software calculates energy balances dynamically taking into account climatic variations and a dynamically varying time-step. And it solves heat balance equations according to the user defined building geometry, construction, HVAC conditions and internal heat loads, with use of measured climate and weather file [23]. In recent years, the accuracy and reliability of the IDA-ICE has been examined in many validation studies [24], [25], so selection of the IDA-ICE as the simulation tool for simulation is well grounded.

2.2 Building model

The studied building, whose IDA-ICE MODEL is shown in Figure 3, is a nine-storey office building located in Gothenburg, Sweden. The building has a total height of 37.3 m and a window-to-wall ratio of 36.3%. It has a north-south orientation and the geometry of the building is an irregular polygon with highly glazed facades. The building contains open office landscapes, group rooms and break rooms, gym, restaurant and an underground garage.

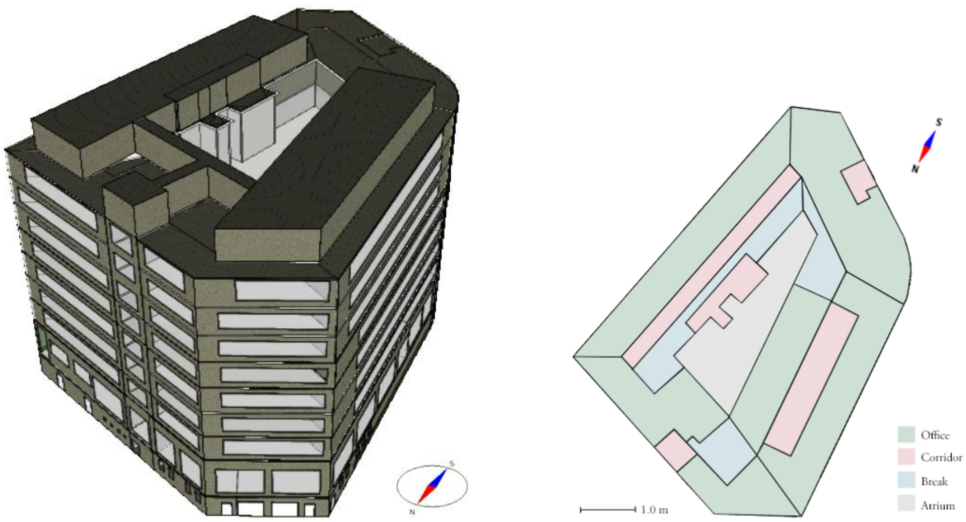


Figure 3 Case building model, IDA-ICE MODEL

The total floor area is 18903 m^2, of which the underground floor area is 1944 m^2. The first to eighth floors is utilized for open office space with a few small break rooms, while the ninth floor houses the building's plant rooms. The center of the building is a stepped atrium starting from the second floor and widening from the fifth floor.

Table 1 shows the construction elements of case building one, including U-value and thickness of opaque constructions, as well as factors of glazing used in the model.

Table 1 Case building one constructions

Element	**U-value, W/(m²•K)**	**Thickness, m**
External walls	0.17	0.280
Internal walls	0.62	0.146
External floors	0.57	0.355
Internal floors	3.50	0.200
Roof	0.16	0.230
Walls below ground	0.49	0.170
Slab towards ground	0.13	0.405

Element	**U-value, W/(m²•K)**	**G-value**	**Emissivity**	**Integrated window shading G-value**
Windows	0.75	0.32	0.837	0.73

The thermal bridges were calculated by considering the total length of different types of joints and multiplying each by its heat loss coefficient. These heat loss coefficients were estimated using typical value suggested in IDA-ICE. The total thermal bridges accounted for approximately 22% of the total heat transfer, and the total U-value of the case building is 0.41 W/(m^2•K). The infiltration of the building was considered as 0.015 L/s of per exterior surface area.

Table 2 The setpoint of each zone

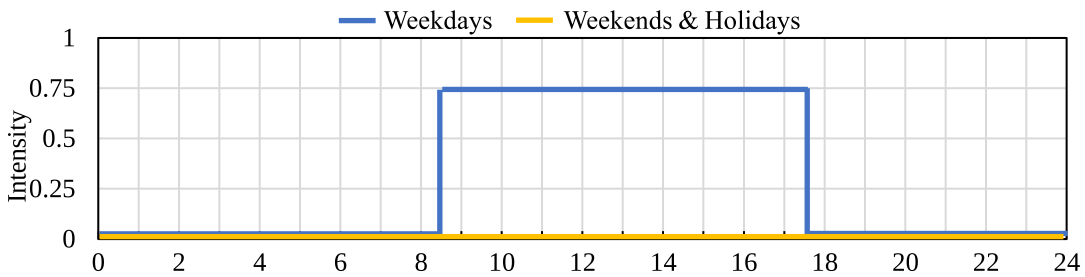
Zone	Heating Setpoint, °C	Cooling Setpoint, °C
Open office landscape	21	24
Group room	21	24
Break room	21	25
Restaurant	21	24
Gym	21	23
Corridor	21	25
Staircases	20	25
Plant room	18	-
Garage	11	-

Temperature setpoint is one of the most important parameters that needs to be achieve by HVAC system. In this study, the building setpoint of heating and cooling of each zone were listed in Table 2. Plant room and garage were not considered as conditioned area during cooling season.

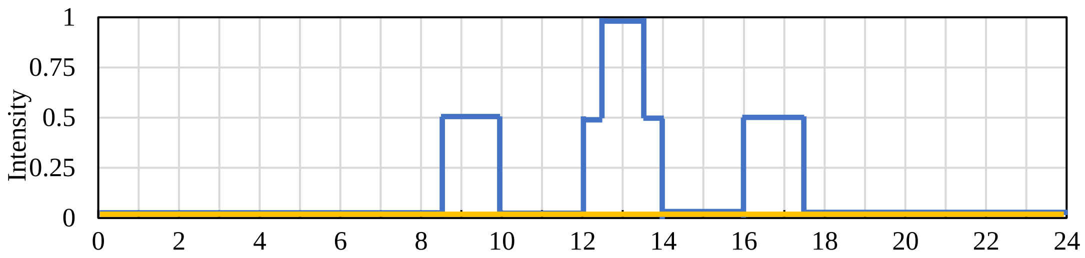
Table 3 Internal heat gain of each zone

Zone	Occupants, No./m^2	Lighting, W/m^2	Equipment, W/m^2
Open office landscape	0.066	5	5
Group room	0.066	5	5
Break room	0.050	2	2
Restaurant	0.050	5	5
Gym	0.050	5	5
Corridor	0.066	2	0
Staircases	0	2	0
Plant room	0	2	0
Garage	0	2	0

The internal loads of these two cases were configured identically, with separate settings applied to each zone based on its specific function. Occupants were modelled with an activity level of 1.2 MET and clothing insulation level of 0.85±0.25 CLO constantly. The following Table 3 presents the internal heat gain of each zone. According to occupancy intensity, the case building accommodates a total of 861 occupants.



(a) Open office landscape, Group room, Corridor



(b) Break room

Figure 4 The schedule of occupants, lights and equipment of main zones of the building: (a) the schedule of open office landscapes, group rooms and corridor; (b) the schedule of the breakroom

Figure 4 illustrates the schedule of the occupants, lights and equipment, where the y-axis represents the intensity of the loads and x-axis shows the hour. The open office landscapes, group rooms and corridor followed the same schedule while the break rooms had different one.

In addition, the schedule for occupants, lights and equipment of each zone was consistent. The usage profiles such as the intense of internal loads and schedule remained unchanged from the original building.

Considering the case building is an office building, they are occupied period from 07:00 to 18:00 on weekdays, so fans and chillers are operational only during these periods.

2.3 Cooling system designs

In IDA-ICE, there were many parameters that need to be defined when design cooling systems. Airflow rates in supply and exhaust parts for different zones in the form of a VAV system were defined, which was controlled by CO_2 level and temperature for each zone. As for CRCP system, panels were selected as room units for each zone, where dimensions, cooling capacity, design conditions and control sensors were defined based on hand calculation using excel sheet. To elaborate, the first step was to determine the total heat that needs to be removed by the panels. Next, compare this heat load with the maximum cooling capacity of the panels to determine the actual number of panels required for each zone. If the maximum cooling capacity of the panels was still insufficient to handle the excess heat, then compensated airflow was calculated. Section 2.3.3 below introduced the equations used to calculate the maximum cooling capacity and the required number of panels in the CRCP system. Furthermore, airflow rates demand in its combined CAV system were introduced with the method in 2.3.1.

2.3.1 Ventilation demand

Ventilation is the process of exchanging indoor air with outdoor air to maintain indoor air quality by removing pollutants, odors, and excess moisture. Proper ventilation is essential for health and comfort of occupants. The minimum ventilation rate is determined as hygienic requirement based on Swedish building regulations, BBR, calculating as equation 1 [26].

$$q = 0.35\ l/(s \cdot m_{floor}^2) + 0.7\ l/(s \cdot person) \tag{1}$$

In addition to hygienic requirements, air also needs to be used to remove excess indoor heat to meet the setpoint in a VAV system, therefore, airflow rate for VAV systems varies with using conditions. Similarly, In CRCP systems, latent heat, mainly produced by occupants, also needs to be removed by airflow. The required airflow rate for dehumidification of each zone was determined by using equation 2 [27].

$$q_L = \rho_{air} \times v \times I_{vap} \times \Delta d \times 10^{-3} \tag{2}$$

Where q_L – Latent heat, W

ρ_{air} – Density of air, kg/m^3

v – Airflow rate, L/s

I_{vap} – Enthalpy of evaporation, kJ/kg

Δd – Moisture content difference, g/kg$_{dry\ air}$

The total latent heat produced by occupants were calculated with equation 3.

$$Q_L = number\ of\ occupants \times q_{L,per\ person} \quad (3)$$

Where $q_{L,per\ person}$ represents latent heat per person.

From 2021 ASHRAE Handbook, latent heat given off by human beings in different states of activity was recommended. For these office buildings, where occupants were considered to moderately active, latent heat was determined as 59 W/per person [28].

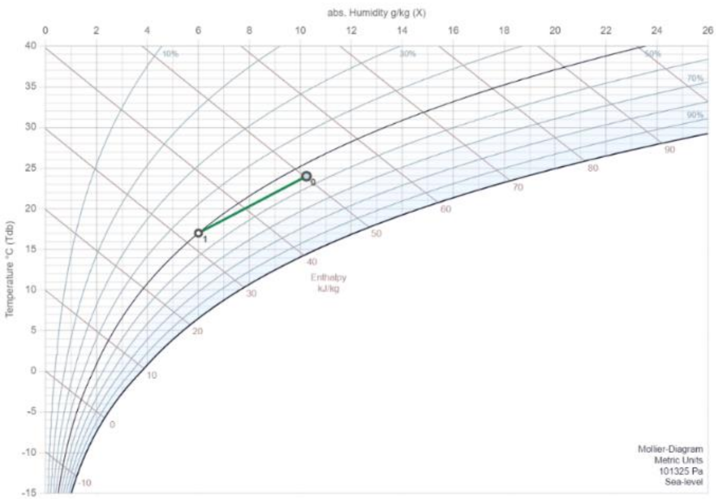


Figure 5 Mollier diagram, shown different air condition points

The enthalpy of evaporation of water was determined as 2454 kJ/kg through an online calculator [29] and the density of air was 1.2 kg/m^3. The moisture content difference was determined through a Mollier diagram, see Figure 5, where the moisture content of room air point (0) and supply air point (1) could be read. As a result, the moisture difference 4.2 g/kg$_{dry\ air}$ was used in the equation 2.

The design airflow rate of the CRCP systems was determined by comparing the airflow rates required for hygiene and dehumidification, with the larger of the two being used.

2.3.2 VAV system - Diffusers sizing

The supply and exhaust airflow rate at critical condition, which means at the time when maximum heat needed to be removed to maintain the desire room temperature setpoint, was established from IDA-ICE simulation. The supply air temperature was set to 16 °C with 1 °C constant rise. After conducting a "Cooling load" simulation, the maximum supply and exhaust airflow of each zone were displayed under "Zones, muti-simulation cooling summary" bar, which were used to dimension the size and quantity of supply and exhaust diffusers for the zones. The quantity of the diffusers was considered with size and layout of the zones as well, with a ratio 3:1 between supply and exhaust diffusers, whose aim is to ensure well-mix of the air to achieve efficient and effective air distribution within a space while ensuring occupant comfort and indoor air quality.

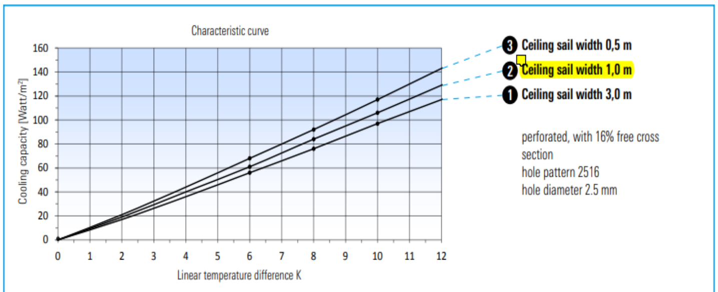
2.3.3 CRCP system - Ceiling radiant cooling panels sizing

To dimension the required cooling capacity of CRCP, the cooling load of CRCP at critical condition is the primary parameter needed. The maximum cooling load requirement was established using IDA-ICE by simulating with ideal cooler only, meaning turn off AHUs. Ideal cooler is an electric room unit whose cooling capacity can be defined and it is not affected by chilled water temperature. From a “Cooling load” simulation, the maximum power requirement of each zone was displayed under “Room unit cool” which regards maximal value of the heat (both sensible and latent) removed from the zone from local units. With subtraction of the sensible heat removed by airflow in CAV system from the total cooling demand, the cooling capacity of CRCP of each zone was determined.

The characteristic curve of CRCP was provided by the manufacturer Aquatherm Company, shown in Figure 6, which illustrates the standard cooling capacity across various temperature differences, with the temperature difference defined as the variance between the mean water temperature and the air temperature.

The required area of CRCP for each zone was calculated by using cooling load divided by the cooling capacity obtained from Figure 6. For example, when the chilled water temperature was at 16/18 °C and the setpoint was 24 °C, the cooling capacity was 84 W/m^2 at 1.0 m ceiling sail width. Additionally, it is considered that the maximum available area is 75% of the ceiling. The actual area of CRCP was determined by comparing the required panel area and the maximum available area.

Standard cooling capacity according to DIN EN 14240: 2004-04



Calculation example for: flow temperature 15° C / return temperature 17° C

Linear temperature difference K	6	8	10
Room temperature °C	22	24	26
① Ceiling sail 0,5 m W/m²	68	92	117
② Ceiling sail 1,0 m W/m²	61	84	106
③ Ceiling sail 3,0 m W/m²	56	76	97

Figure 6 Characteristic curve of the CRCP at 1.0 m ceiling sail width [30]

If the required area is less than the maximum available area, then the required area is the actual area. Conversely, if the required area exceeds the maximum available area, it indicates that the

CRCP cannot fully handle the load. In such cases, compensated airflow was necessary to be determined to remove the excess heat by using equation 4.

$$Q_e = \rho_{air} \times v' \times \Delta T \tag{4}$$

Where Q_e – Excess cooling load, W

v' - compensated airflow, L/s

ΔT – Temperature difference between setpoint and supply air temperature

The grid length dimensions, from Aquatherm company [29], range from 400 mm to 5000 mm, with a minimum grid width of 240 mm and a maximum grid width of 1000 mm. To optimize investment costs, CRCP was determined based on fixed dimensions. The number of CRCP units required for each zone was calculated by dividing the actual area by the standard CRCP area of 2.4 m² (corresponding to dimensions of 800 mm x 3000 mm). The standard cooling capacity of CRCP was presented in Table 4.

Table 4 Standard cooling capacity of CRCP of different zone setpoint.

T_{zone}, °C	23	24	25
$T_{water\ mean}$, °C	17	17	17
CRCP cooling capacity, W/m²	60	72	84

After calculations, the ceiling panels were added for each zone in IDA-ICE, where the design power, the design temperature conditions, the sensor, and dimension for each panel were determined based on the previous calculation results. The air temperature sensors were used so that the simulation results would be comparable with those of VAV system. And air temperature sensor is common and economical as well.

2.4 Parametric studies

In addition to BASE cases, four additional cases were studied and compared in this project. Two of these cases focused on internal heat gain changes while the other two studied external heat gain changes, named case IN1, IN2, EX1, EX2 respectively.

Internal loads of buildings were chosen as studied parameters, and their variations were displayed in Table 5 as follows.

Table 5 The internal loads variations.

	Occupancy, No. /m²		**Lighting, W/m²**		**Equipment, W/m²**	
	Office rooms	Others	Office rooms	Others	Office rooms	Others
IN1	0.095	0.065	7	3	12	4
IN2	0.11	0.08	9	4	19	6

The G-value of windows of the buildings was another studied parameter, where G-value of glazing increased from 0.32 of BASE to 0.64, 0.99 for EX1, EX2 respectively. There was an integrated window shading with a G-value 0.73, so the comprehensive G-value of windows were 0.23, 0.47, 0.72 respectively.

2.5 Thermal comfort analysis

The room air temperature and operative temperature are the measures examined by using IDA ICE to analyze the thermal comfort. Operative temperature is a measure used to assess the thermal comfort experienced by occupants within a space. Unlike air temperature, which only considers the temperature of the air, operative temperature takes into account both air temperature and radiant temperature, providing a more comprehensive evaluation of the perceived thermal environment. Therefore, operative temperature was used as a more accurate indicator of thermal comfort analysis. In order to make sure there is no overheat during the whole conditioning period, the ‘critical week’ was determined and the average temperature of the ‘critical week’ was used to analysis the thermal comfort. The 'critical week' refers to the hottest days of the year, during which the cooling system must remove the greatest amount of excess heat. The ‘critical week’ occurs at the end of June - the beginning of July (6.25-7.6).

In addition, the online CBE Thermal Comfort Tool was used to analyze thermal comfort of the building. This web-based tool predicts thermal comfort according to standard ASHRAE-55, including the combined PMV-PPD model [31], with visualizations of comfort boundaries within psychrometric charts [32] The example page is shown below, Figure 7 In this psychrometric chart the abscissa is the operative temperature and the comfort zone represents the combination of conditions with the same DBT and MRT for which the PMV is between -0.5 and +0.5, according to the standard [33].

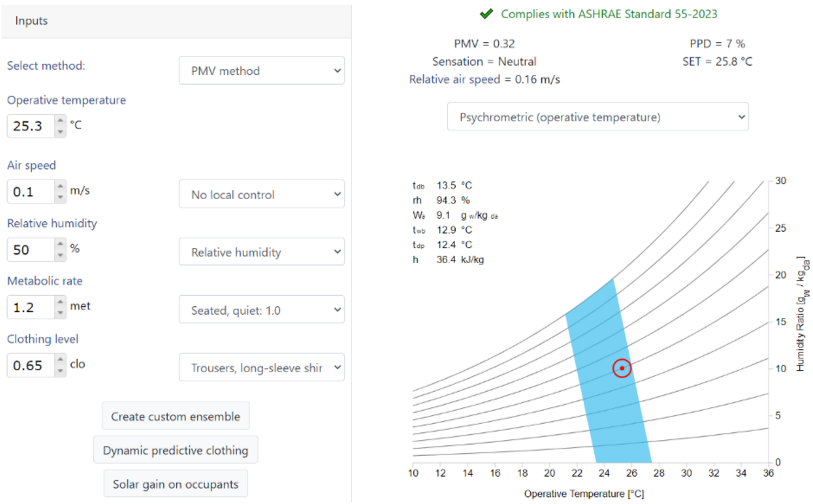


Figure 7 The page of CBE Thermal Comfort Tool

The clothing level insulation 0.65 clo was used, because the highest percentage of clothing insulation values were distributed to 0.65 clo in Summer [34].

Southern and Eastern zones on the third floor were taken as typical zones to analysis thermal comfort. The critical week's conditions were then employed to analyze thermal comfort within these zones. Finally, the top-right section of the page provided the results of the input conditions.

2.6 Climate data

Gothenburg, Sweden, the location of the case building, belongs to Cfb climate zone according to the Köppen climate classification [21]. The weather file of Gothenburg from ASHRAE IWEC2 was used as the current climate conditions.

To perform the impact assessment of climate change on the energy performance of the building, the method suggested by Nik [35] was applied. The method is based on synthesizing three weather data sets for each 30-year period: (1) typical downscaled year (TDY), (2) extreme cold year (ECY) and (3) extreme warm year (EWY). Each weather data set is created based on comparing the cumulative distribution of the outdoor (dry-bulb) temperature and finding the typical and extreme months. In this work, Typical downscaled year (TDY) weather set was used for sizing the system and analysis the building's energy performances in the future, because TDY represents the typical conditions during the considered period (2040-2069).

However, studies revealed that assessing the energy performance of the building only under typical future conditions is not sufficient due to the challenge of climate uncertainties. Moazami et al. [36] evaluated the impacts of extreme conditions on the energy performance of all 16 ASHRAE standard reference buildings and a virtual neighborhood. The results show an increase of 2–28.5% in peak load for cooling demand under extreme conditions, compared to typical conditions depending on the building type. Therefore, the sizes were estimated to increase by 20% to overcome the extreme conditions. After sizing, the EWY weather set was used for simulation again, which employed a time step of one hour, allowing for tracking of the cooling energy on a per-hour basis. From the detailed results, the power demand per hour of the VAV and CRCP system was obtained and the maximum value represents the cooling peak power of VAV and CRCP system under extreme warm conditions. By comparing the results from the simulations using the TDY weather set with those from the EWY simulation, the cooling peak power of the VAV and CRCP systems under future climate conditions was obtained. The same method was applied using the ECY weather data to determine the heating peak power of the VAV and CRCP systems.

Regarding the annual energy consumption, the TDY file was used for simulations, whose validity has been proved: the cumulative distribution of the heating and cooling demand using TDY are very similar to the original weather data set [35].

Furthermore, the EWY weather set was used together with TDY to analysis the thermal comfort of the building, in order to verify whether the cooling capacity of room units can satisfy the rooms requirement, even under extreme conditions.

2.7 Life cycle cost analysis (LCC)

The life cycle cost (LCC) associated with the cooling systems was calculated to get cost-effective mechanical cooling system design. LCC was done through the net present value (NPV) method which is considered to be the most widely used method, presented as equation 5 [37].

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{5}$$

Where NPV – Net Present Value of life cycle costs

C_t – Sum of all relevant costs after the reduction of revenues created in period t

r – Discount rate

t – Monitored period

T - Life cycle duration

NPV is the result of the application of discount factors, based on a required rate of return to each year projected cash flow, both in and out, so that the cash flows are discounted to present value [38]. To treat cost as positive, the best choice between several competing alternatives is the one with minimum NPV consequently [39].

The LCC analysis considered initial investment, maintenance costs and operation costs of the mechanical cooling systems throughout their lifespan or service period. The operational costs, which include peak power, energy, and HVAC auxiliary costs, were detailed in the following section. In this project, the calculation period was set to 20 years with a discount rate 6% given by the Riksbank. The calculations were made in Swedish kronor (SEK). In addition, considering the uncertainty of future discount rates and their impact on LCC, sensitivity analysis was conducted with the discount rate ranging from 1% to 10%.

2.7.1 Investment and maintenance

The investment costs and maintenance costs were estimated by experience values, provided by the company Bengt Dahlgren. The reference values of both investment costs and maintenance costs were presented in Table 6 below.

Table 6 The reference values for calculating investment and maintenance costs.

Investment costs, SEK/m^2			**Annual maintenance costs**		
	VAV	CRCP		VAV	CRCP
Heating system	460	460	Heating system	1.0%	1.0%
Cooling system	200	680	Cooling system	0.5%	2.0%
Ventilation system	1600	1250	Ventilation system	2.5%	1.5%
Control system	385	320	Control system	2.0%	1.0%

The accounted investments include heating, cooling, ventilation and control systems with their reference values given in the cost per floor area, SEK/m^2. In addition, the annual maintenance costs of all these systems were taken into consideration, which were calculated as a percentage of the investment cost of each system.

2.7.2 Energy, power and electricity

The energy and power costs were sourced from the supplier company Göteborg Energi [40].

Table 7 Monthly energy cost of district heating and district cooling

District Heating		**District Cooling**	
Month	**Energy (SEK/MWh)**	**Month**	**Energy price (SEK/MWh)**
January	531	January	145
February	531	February	145
March	531	March	145
April	366	April	243
May	167	May	326
June	102	June	344
July	102	July	344
August	102	August	344
September	148	September	344
October	366	October	291
November	422	November	247
December	531	December	145

Table 8 Power cost of district heating and district cooling

District Heating			**District Cooling**		
Three-day average power (kW)	**Fixed price (SEK/year)**	**Variable price (SEK/kW, year)**	**Max Power (kW)**	**Fixed price (SEK/year)**	**Variable price (SEK/kW, year)**
0-100	10360	1089	0 - 100	21380	881
100-250	15260	1040	100 - 250	37580	719
250-500	28260	988	250 - 500	75830	566
500-1000	55260	934	500 - 1000	112830	492
1000-2500	110260	879	> 1000	137830	467
> 2500	252760	822			

The annual cost of district heating and district cooling consists of energy cost and power cost. The energy cost varies monthly, which is presented in Table 7. The power cost includes a fixed price which is determined by the peak power and a variable cost for the total power need, shown in Table 8. The current electricity price is 1.4 SEK/kWh. Future district heating and district cooling costs were calculated with a price growth rate of 1% and electricity price was calculated with a growth rate of 2%.

A manual calculation was employed to obtain AHU auxiliary energy. It was calculated by multiplying the annual airflows with the specific fan power (SFP) of the fans in AHU. The SFP value of newer systems is typically 1.5 kW/(m^3/s), and this value was used for calculations. The annual airflows of the AHU were determined using IDA ICE and displayed in a duration diagram and hourly value table.

3 System Design

This chapter provides the design results of CRCP systems in various scenarios, following the method introduced in chapter 2.3, including the number of panels required, the necessary compensated airflow, and the total airflow results.

The investigation considered multiple scenarios representing different external and internal loads, as well as climate conditions. Table 9 summarized the number of panels needed for each scenario, accounting for variations in cooling load demands and panel sizes within the building space except the plant rooms.

A total of 1076 standard sized ceiling panels were required, and the minimum airflow requirement in the BASE case was 8657 L/s. The detailed sizing results of the CRCP systems for each zone in all cases are presented in Appendix A.

Table 9 The CRCP system designs, showing the number of units and total airflow rate in different scenarios.

	BASE	**EX1**	**EX2**	**IN1**	**IN2**	**FUTURE**
Number of panels, st	1076	1775	2012	1496	1860	1663
Compensated airflow, L/s	0	5198	19261	243	1198	4027
Total airflow, L/s	8657	13856	27919	10418	12336	12684

Notably, the BASE case does not require compensated airflow. However, in all other scenarios, different levels of compensated airflow are necessary due to increased cooling demands, resulting in higher total airflow. Particularly in case EX2, the compensated airflow exceeds twice the total airflow of the BASE case. The primary zones requiring high compensated airflow are the occupied landscape offices facing east and west. The reason for this difference is that because high g-value windows obtain a large amount of solar heat but the ceiling area available for panel installation is limited, the cooling capacity of the panels in these areas does not meet the needs.

4 Results

This section provides the simulation results and analyzes the underlying reasons, including energy and cost performances of the VAV and CRCP systems. The results for the BASE case, along with cases with different internal loads and external loads, are presented in 4.1 and 4.2 in turn. Comparisons between the VAV and CRCP systems are conducted for all cases. In addition, section 4.4 presents a comparison of results between future climate scenarios and current climate scenarios.

4.1 Energy and cost results of BASE case

4.1.1 Building energy demand

The case building's energy and peak power demands under current climate conditions are presented in Figure 8. The left vertical axis of bar chart is building's energy demand, and the right vertical axis represents the building's peak power demand.

Building heating demand refers to the total amount of heat that needs to be provided by a heating system, and building cooling demand is an indicator used to measure the amount of heat that the cooling system needs to remove to keep the indoor temperature stable under certain conditions.

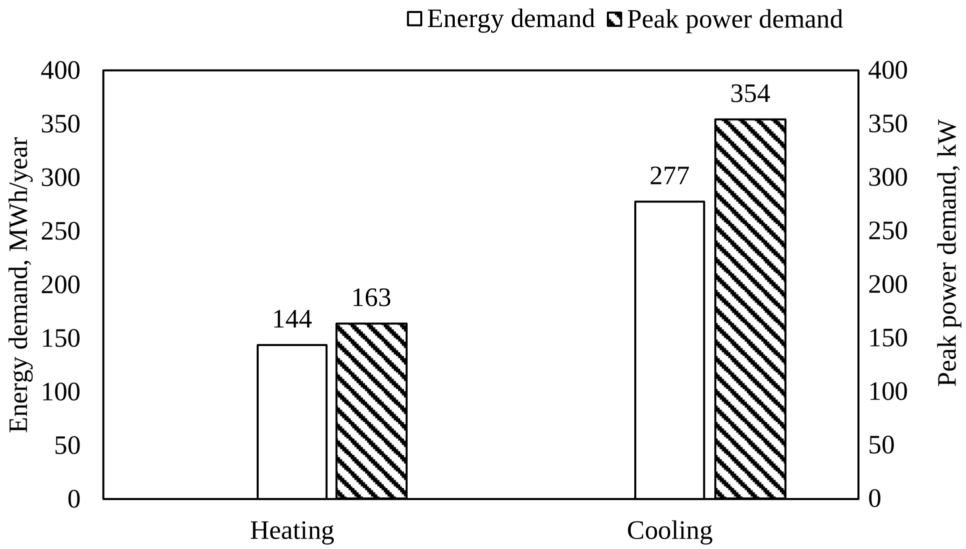


Figure 8 The energy demand and peak power demand of the building.

The heating energy demands are lower than cooling demands because the case building is well-insulated with large windows, leading to low heat loss and more solar heat gain. However, it also means larger heat gain during summer, coupled with internal heat gains, thus the cooling demand is high.

Notably, the building's energy demands remain consistent regardless of the type of HVAC system used. This is because the energy demands of the building are determined by its characteristics (e.g. insulation, windows, orientation) and its usage profile (e.g. occupancy levels, operational hours), rather than the specific HVAC system installed.

4.1.2 Energy analysis of the VAV and CRCP systems

Figure 9 show the peak power of the base case of VAV and CRCP systems, covering heating and cooling demand of the AHU and zone units.

Although the AHU heating and zone heating power demands of VAV and CRCP systems are nearly identical, a notable difference arises in their cooling peak power. The CRCP system registers a lower cooling peak power at 456 kW compared to the VAV system's 633 kW, which is much closer to the building’s own demand. It is because VAV system only cools the air by convection while CRCP system primarily rely on water as medium and use surfaces to remove heat from zones through radiation and convection, which is more efficient since water has a higher thermal conductivity and specific heat capacity compared to air.

Remarkably, the AHU power of the CRCP system amounts to only around 27% of that required by the VAV system. This efficiency is achieved because the sensible loads is handled by panels, leaving the AHU to handle only the latent loads and ventilation, resulting in a significantly lower airflow rate.

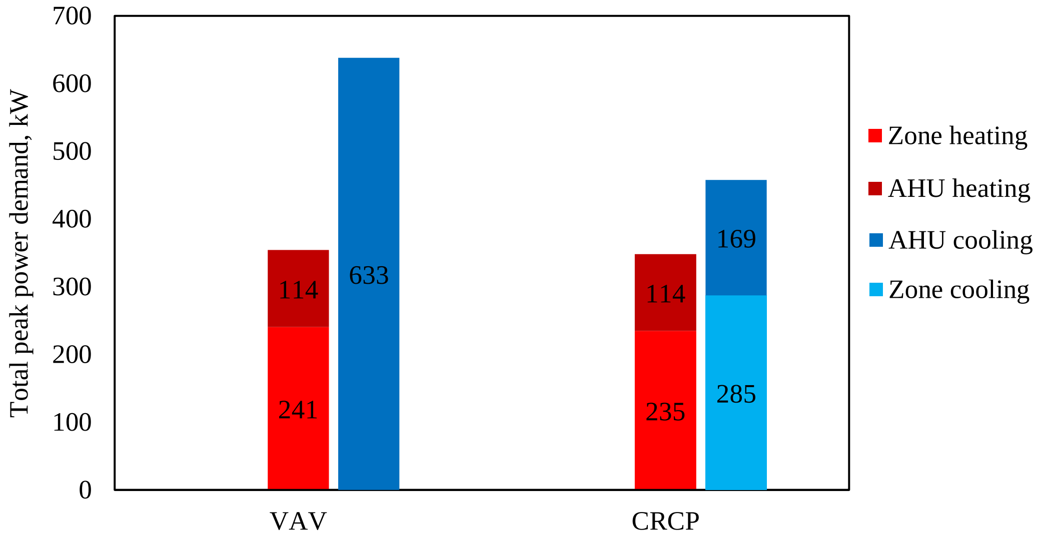


Figure 9 Heating and cooling peak power of BASE case.

In terms of purchased energy, district heating, district cooling and AHU auxiliary electricity are compared. The district cooling energy includes energy used by AHU and zone unit (panels for CRCP system), named AHU cooling and Zone cooling respectively. And the same applies to district heating.

As shown in Figure 10, the district heating energy consumption are almost the same for VAV system and CRCP system, because both systems use the same heating methods. Moreover, the supplied airflow is maintained only for hygienic ventilation reason during the winter, with no need for compensated airflow in CRCP system for BASE case.

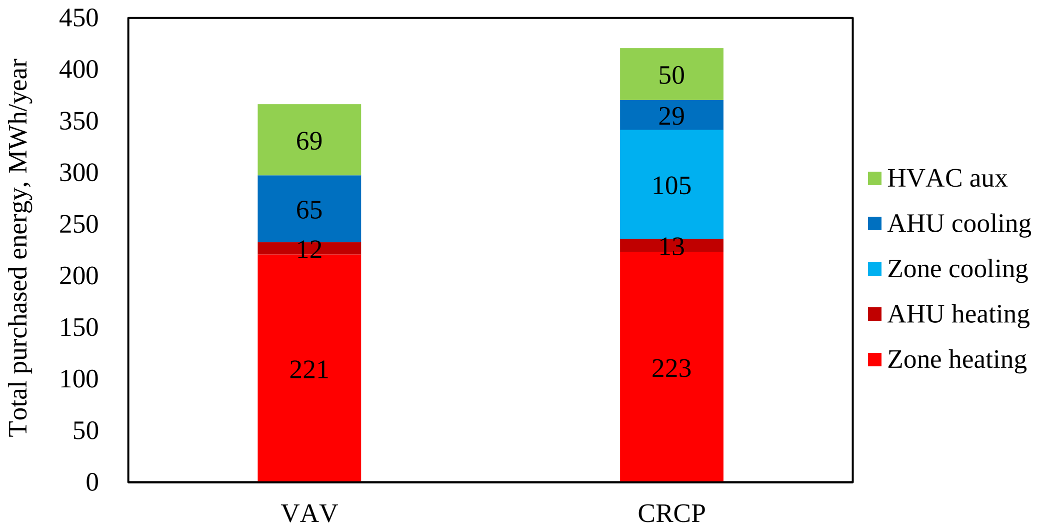


Figure 10 Total purchased heating, cooling and AHU auxiliary energy

When it comes to district cooling, the CRCP system has significantly lower AHU cooling energy, with less than half of that the VAV system requires, due to significantly lower airflow. Meanwhile, lower AHU cooling energy leads to lower AHU auxiliary energy, which is 50 MWh/year of CRCP system compared to 69 MWh/year of VAV system.

However, the CRCP system requires a higher total purchased cooling energy compared to the VAV system, with annual consumption of 134 MWh and 65 MWh respectively. The difference is because the VAV system can utilize more free cooling during cool seasons. When the outdoor temperature is below the zone cooling setpoint, the VAV system changes the mechanical cooling to bring cool ambient air directly into the building through AHU, bypassing the need of refrigeration system thus reducing cooling energy consumption. In contrast, the CRCP system relied on chilled water produced by refrigeration systems at all times, which leads to higher purchased cooling energy.

4.1.3 Life-cycle costs

The investment cost of VAV system is 49,998,435 SEK, while the CRCP system needs a slightly higher investment cost of 51,227,130 SEK. On the contrary, the CRCP system commands an approximately 25% reduction in annual maintenance cost compared to VAV system 1,007,530 SEK per year.

Figure 11 shows the present value of annual energy and power costs for two systems, where heating, cooling and electricity costs are marked in red, blue and green respectively. The cost of power consists of a fixed price and a variable price determined by the peak power.

Overall, the power cost significantly influences the annual total energy costs for both VAV and CRCP systems, accounting for over 75% of the total costs. Moreover, the impact of the fixed cost is considerate as it constitutes nearly 30% of the total power cost for cooling for both systems.

When comparing two cooling systems, the annual energy costs of CRCP system is lower than those of VAV system, with a difference of 5.2 SEK/m^2, meaning a total saving of about 97,000 SEK. The primary savings are achieved in cooling power due to a lower cooling peak power required though its annual cooling energy cost is slightly higher.

Furthermore, the fan energy savings achieved by CRCP system due to significantly reduced airflow are evident in its lower electricity cost, 3.7 SEK/m^2 compared to 5.1 SEK/m^2.

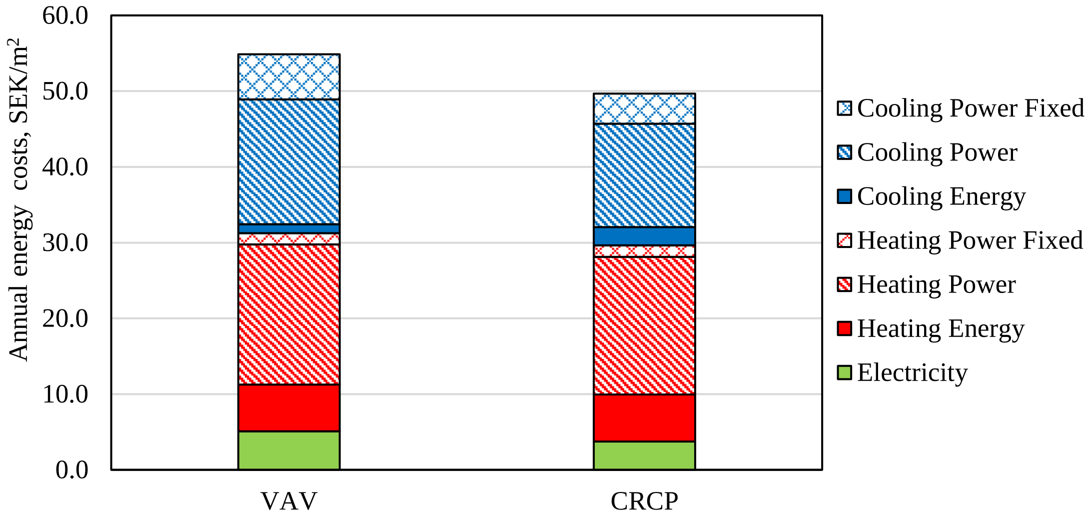


Figure 11 Annual total energy costs, Preset Value.

The LCC results of BASE case are presented in Figure 12, including initial investment, maintenance costs and total energy costs of the systems throughout 20 years. The majority of LCC is initial investment, which is 67% for VAV system and 72% for CRCP system. Moreover, maintenance and power costs are also important components in LCC.

CRCP system leads to 150 SEK/m^2 lower LCC compared to VAV system and the primary cost savings stem from reduced maintenance and power costs although CRCP systems require more costs for cooling energy. Therefore, the CRCP system is a cost-efficient alternative cooling system.

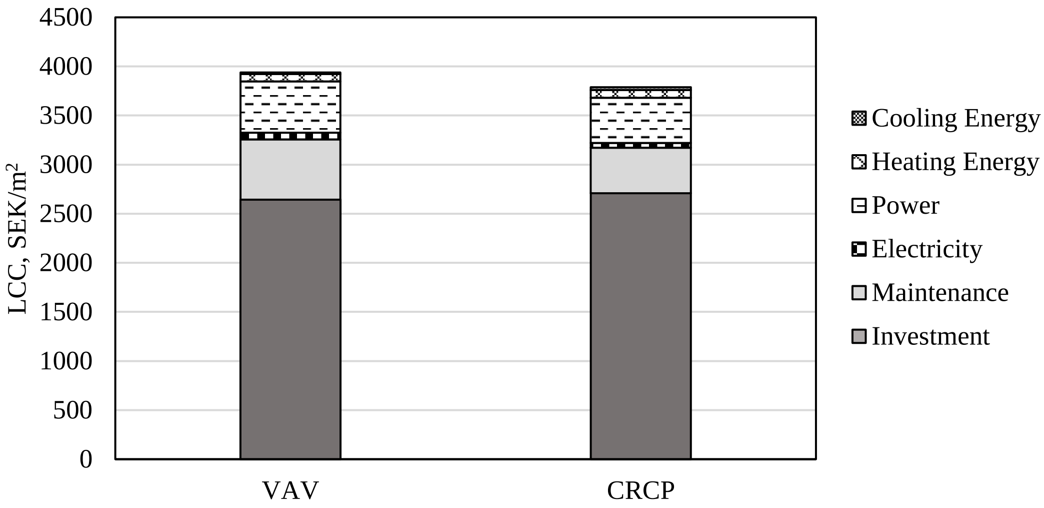


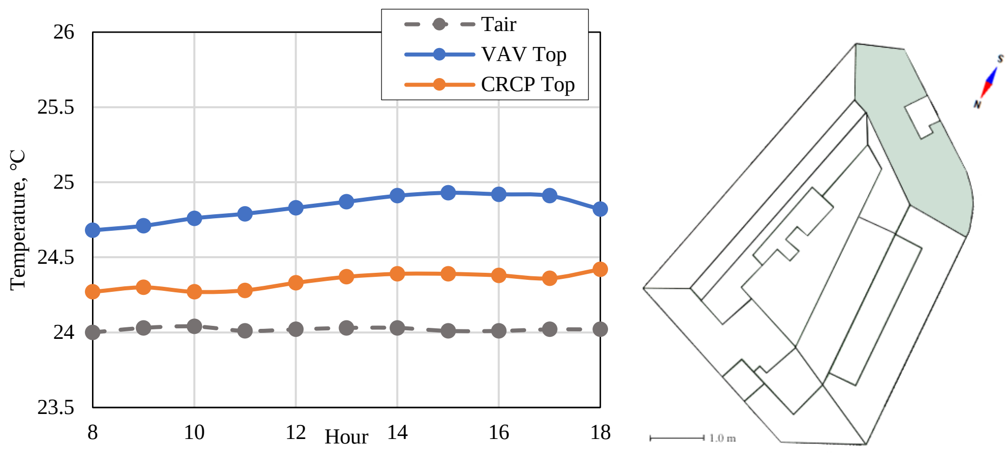
Figure 12 The LCC results of BASE case

4.1.4 Thermal comfort analysis

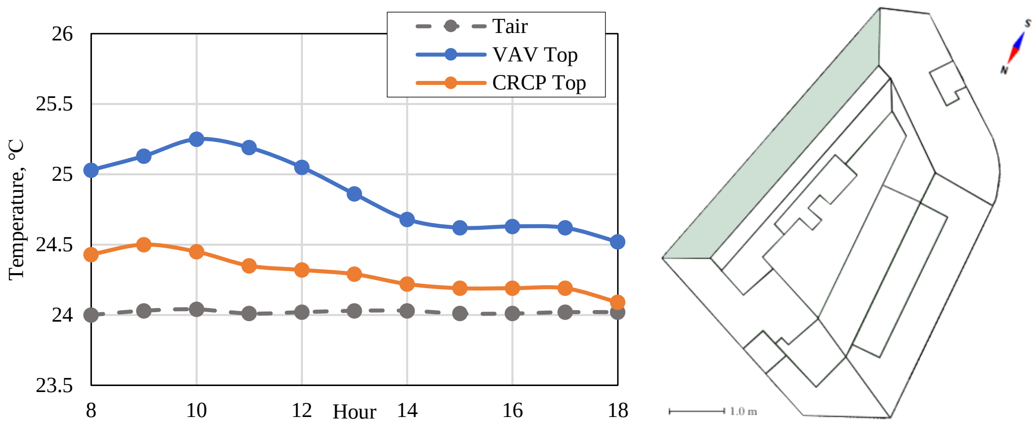
The room air temperature and operative temperature of VAV system and CRCP system under current climate conditions are compared in Figure 13, where the results of two typical zones facing South and East are named as (a) and (b) respectively. In Figure 13, the average room air temperature of the 'critical week' is shown in dashed lines, which are the same for VAV and CRCP system due to air temperature sensor control was used for both. The average operative temperature of the 'critical week' of VAV system is shown in blue series, while orange series represents the temperatures of CRCP system.

In all scenarios and for both systems, the room air temperature consistently remains at 24 °C and lower than the operative temperature throughout the occupied hours 08-18. However, the operative temperature exhibits different fluctuations for two systems for both zones. Specifically, in VAV system, the southern zone's operative temperature is 24.6 °C at 8 a.m., climbing to its peak of 24.9 °C at 3 p.m., which is because the zone obtains more solar radiation in the afternoon as the sun moves. Conversely, the eastern zone has an opposite tendency. It attains more sun radiation in the morning, leading to a slightly higher temperature around 10. a.m. Furthermore, it is evident from these findings that there is consistently at least a 0.5 °C difference between air temperature and operative temperature for the VAV system.

On the contrary, CRCP system displays a slightly different pattern. Unlike VAV system, the operative temperature in CRCP system closely tracks the air temperature fluctuations for all zones. For zones facing South, the operative temperature of CRCP system register around the 24.4 °C with slightly rise in the afternoon while the operative temperature of the eastern zone decreases from 24.5 °C in the morning to 24.1 °C by 6 p.m. due to the varying intensity of solar radiation.



(a)



(b)

Figure 13 Air temperature and operative temperature of VAV and CRCP systems at the critical design day during occupied hours 08-18. Two different typical zones with different orientation are analyzed: (a) South; (b)East.

Throughout the observation period, the difference between the air and operative temperatures for CRCP system remains consistently around 0.3 °C. As a result, the operative temperature of CRCP system consistently remains lower than that of the VAV system and its fluctuation notable smaller in comparison, which is because CRCP system radiate heat through ceiling and exchange directly with people, resulting in the lower sensation temperature of people. Furthermore, the ceiling, which is made of high thermal mass material, adds inertia and allows to absorb and release heat over a longer period, resulting in more stable operative temperature.

As operative temperature accounts for the combined effects of radiant heat exchange, air movement, and humidity levels on human comfort, it is believed to be a more accurate indicator of people's feelings within the zones. Lower operative temperature and smaller fluctuation indicates a better thermal comfort provided by CRCP system compared to VAV system.

By using CBE Thermal Comfort Tool, the results show that the indoor condition of all zones complies with ASHRAE Standard 55-2023 for both systems. The occupants experience a neutral thermal sensation within the zones.

4.2 Parametric studies results

This section discusses the results of parametric study, which encompasses analyzing the peak power demand, purchased energy of VAV and CRCP systems, and life cycle costs across cases studies examining variations in both internal and external loads.

4.2.1 Internal loads study results

Figure 14 displays the system peak power of case IN1 and IN2, compared with BASE case, and comparison of VAV and CRCP systems of each case.

The cooling peak power of VAV system exhibits a linear increase with rising internal loads, whereas the heating peak power remains constant regardless of internal load changes, which is because internal heat gains are considered in calculating the cooling load but not in the heating load. However, regarding CRCP system, increasing internal loads leads to an increase in both heating and cooling peak power, due to limited ceiling areas caused increasing airflow. For cooling, the limited ceiling area means that when the CRCP cannot remove all the excess heat in the zone, compensation airflow is required. As internal loads increase, the demand for compensation airflow rises to ensure optimal room temperature. Similarly, in heating scenarios, both AHU power and zone power increase due to larger cool air volume requiring more reheat.

The VAV system exhibits a lower heating peak power compared to the CRCP system in both scenarios IN1 and IN2. However, when it comes to cooling, the VAV system's peak power surpasses that of the CRCP system significantly across all cases, with the same reason as in BASE scenario: the CRCP system rely on water to remove excess heat by radiation and convection and water has higher heat capacity than air.

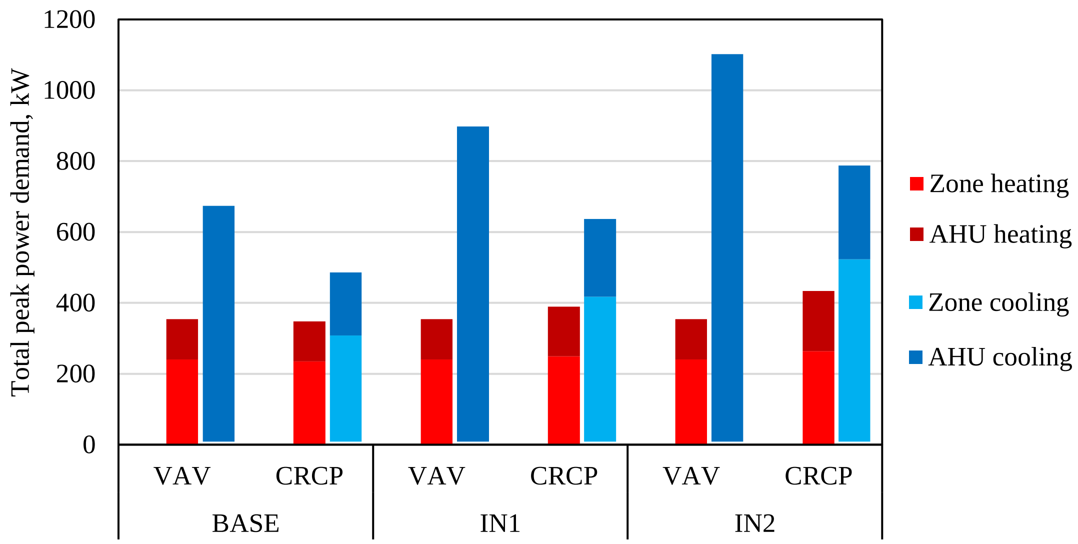


Figure 14 Heating and cooling peak power of cases with different internal loads.

Notably, the AHU cooling power of the CRCP system remains below 30% of the VAV system, with a slight decrease in proportion as internal loads increase due to more panels are used in the center zones of the building without increasing airflow. Compared to the BASE case, the proportions in scenarios IN1 and IN2 are reduced by approximately 2% and 2.5%, respectively.

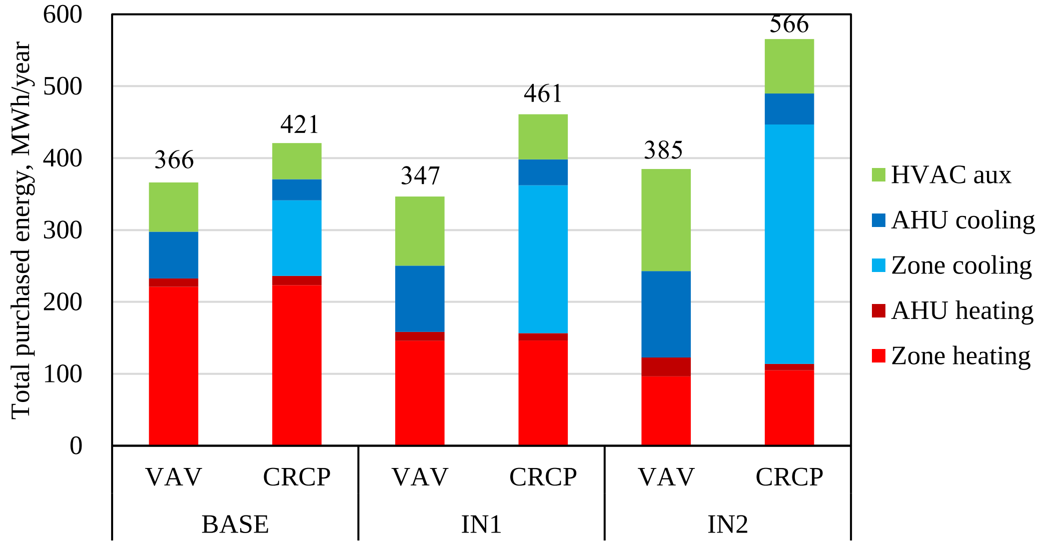


Figure 15 Total purchased heating, cooling and AHU auxiliary energy of cases IN1 and IN2, compared with BASE.

The total annual purchased energy of the CRCP system of case IN1 and IN2 is always higher than that of the VAV system, with the difference becoming increasingly evident as internal loads increase, shown in Figure 15. It is because of the increased use of ceiling cooling panels which always require chilled water during operational period. The district heating energy consumption remains consistently similar between the two systems across all cases, decreasing as internal loads increase. Moreover, it is worth noting that AHU heating energy in VAV system is higher than in CRCP system in IN2, which is because extreme high internal loads cause some rooms such as the gym to need cooling in winter, thereby increasing the airflow. However, the outdoor temperature is low, so more energy is needed in the heating coil.

On the other hand, with increased internal loads, the purchased cooling energy requirement increases rapidly. Especially for CRCP system, cooling energy becomes the dominant in case IN1 and IN2, comprising 52% and 64% of the total purchased energy. Furthermore, the majority of increased cooling energy of CRCP system occurs in Zone cooling, meaning the energy transferred by panels, while less increase from AHU cooling energy. Increasing cooling capacity of panels yields more zone cooling energy and the increase of AHU cooling energy is because of the higher compensated airflow rate, resulting in higher total airflow.

Similar to BASE case, although the total purchased cooling energy for CRCP system is much higher than VAV system, its AHU cooling energy is significantly low due to lower airflow. The AHU cooling energy of CRCP system only accounts for 39% of that of VAV system in case IN1 and its value even decreases to 36% in case IN2. Furthermore, a significant reduction in

AHU energy consumption results in corresponding savings in AHU auxiliary electricity as well. In conclusion, higher internal loads correspond to greater potential for savings in AHU cooling energy and auxiliary electricity.

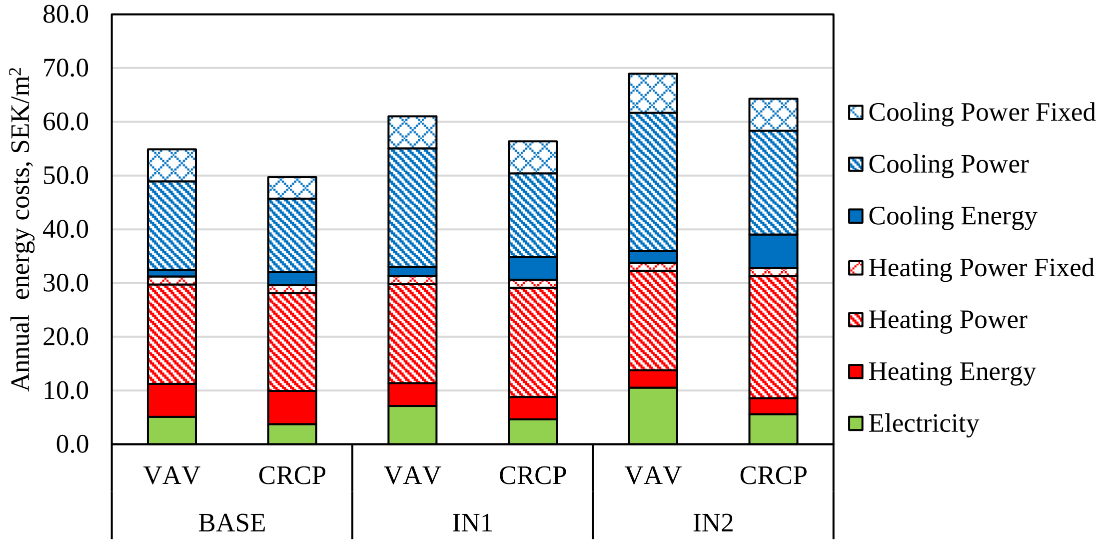


Figure 16 Annual total energy costs of case IN1 and IN2, Preset Value.

In term of the cost analysis, Figure 16 illustrates the annual energy and power costs of two systems for cases with different internal loads, where heating, cooling and electricity costs are marked in red, blue and green respectively as the same with BASE. The cost of power consists of a fixed price and a variable price determined by the peak power.

Overall, the CRCP system consistently maintains lower annual energy costs compared to the VAV system as internal loads increase, showing a difference of 4.6 SEK/m^2 for case IN1 and IN2, although this difference has a slight decrease compared to BASE. Furthermore, with increasing internal loads, both VAV and CRCP system show a rise in cooling power and energy costs, which is the same trend of total energy costs. However, there is a contrast in heating cost between the two systems: while VAV experiences a decrease, CRCP sees an increase.

The majority share of the total annual energy costs is attributed to the power cost, accounting for more than 75% of the total costs. Compared with VAV system, CRCP system stands out for its lower cooling power cost, but it incurs slightly higher heating power costs in both case IN1 and IN2. In addition, the fan energy savings can be achieved by CRCP system due to its lower electricity cost, and the benefit that becomes more obvious with higher internal loads.

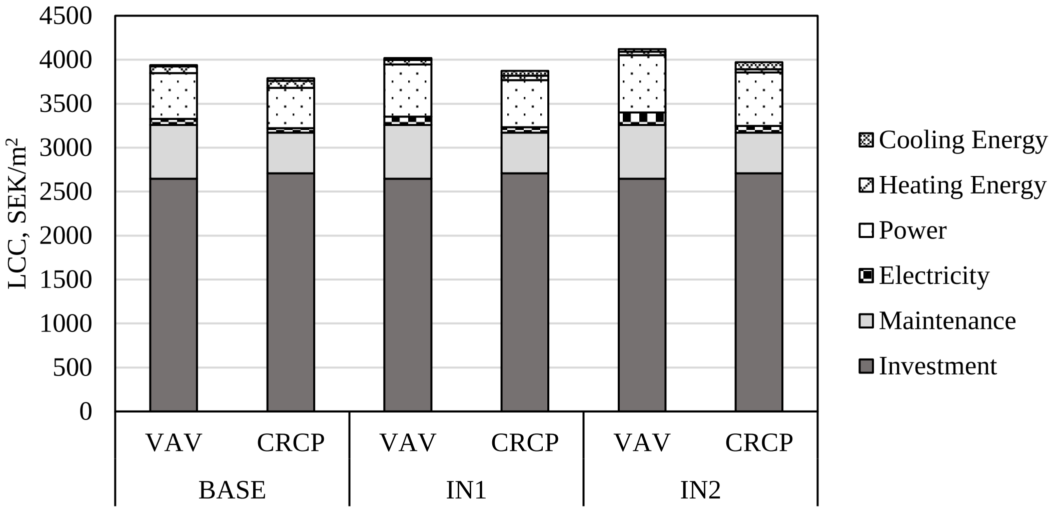


Figure 17 The LCC results of case IN1 and IN2, compared between VAV system and CRCP system.

Initial investment is the primary cost for both VAV and CRCP system in all scenarios, as shown in Figure 17. The LCC results over 20 years of CRCP system is always lower than the VAV system, with the main benefits stemming from reduced maintenance and energy costs. As a result, CRCP system is worth investing in all case BASE, IN1 and IN2.

4.2.2 External loads study results

Similar with Figure 14, Figure 18 illustrates the system peak power of case EX1 and EX2, comparing the results between VAV and CRCP systems of each case.

As the external load increase, the cooling peak power of VAV system exhibits a linear increase, while the heating peak power remains constant, which can be explained based on the peak load calculation methods: the cooling peak load calculation took into account solar heat gain, which is affected by g-value – the varied parameter; but g-value is not considered in the heating peak load calculation.

The results of CRCP system are different in that both heating and cooling peak power increase with increasing external loads. In more detail, both AHU and zone cooling power increases, because increasing external loads lead to more excess heat, resulting in the need of compensation airflow when the maximum CRCP capacity cannot satisfy the setpoint of the zones. Similarly with cooling, the increase of compensation airflow leads to an increase in heating peak power as well. It is notable that the increase of heating peak power of CRCP system is not follow the linear tendency, seen Figure 18. AHU cooling power of CRCP system has an accelerating increase trend, with the AHU heating power representing 32%, 45%, and 60% of the total heating peak power for cases BASE, EX1, and EX2 respectively.

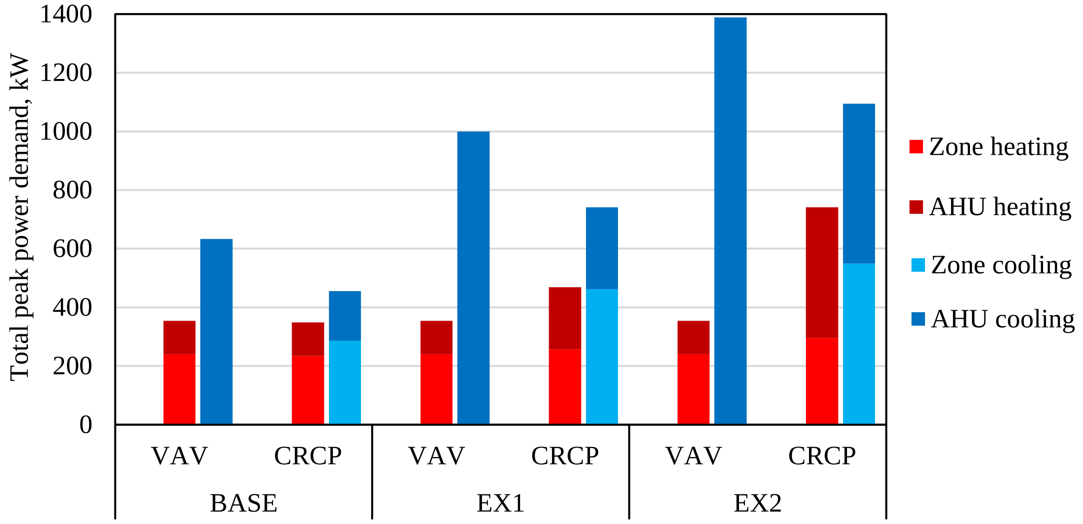


Figure 18 Heating and cooling peak power of cases with different external loads.

The CRCP system exhibits a lower cooling peak power compared to the VAV system in all scenarios. But for heating peak power, although the results of VAV and CRCP systems are nearly identical for case BASE, case EX1 and EX2 require higher heating peak power. It is because it is no need of compensation airflow for BASE. Therefore, it could be noticed that as long as compensation airflow requires, the heating peak power of CRCP system will be higher compared to VAV system.

The total annual purchased energy of the CRCP system of case EX1 and EX2 is higher than that of the VAV system, shown in Figure 19. The difference between the two systems becomes increasingly evident as the external load increases, where case EX2 needs to purchase almost twice as much energy as the VAV system, with the value of 913 and 474 MWh per year.

The total purchased heating energy of VAV system decreases as external loads increase. However, in the case of the CRCP system, while there is a slight decrease of 9 MWh per year for case EX1 compared to the BASE 236 MWh/year, it increases to 292 MWh/year for case EX2. It can be attributed to significantly higher compensation airflow, resulting in more frequent air exchange and more reheat energy during winter. Moreover, the primary energy consumption part is heating in BASE case, but it changes into cooling in case EX1 and EX2. This shift occurs because as external loads increase, more heat is obtained during winter, while in summer, there is a greater need to remove excess heat from the zones.

In terms of cooling, the purchased cooling energy increases rapidly of both systems as external loads increase. Most of the increased cooling energy of CRCP system occurs in Zone cooling, meaning the energy transferred by panels, while less increase from AHU cooling energy. Like BASE case, although the total purchased cooling energy for CRCP system is much higher than VAV system, its AHU cooling energy is significantly low with low airflow, and thus leads significant savings in AHU auxiliary electricity as well.

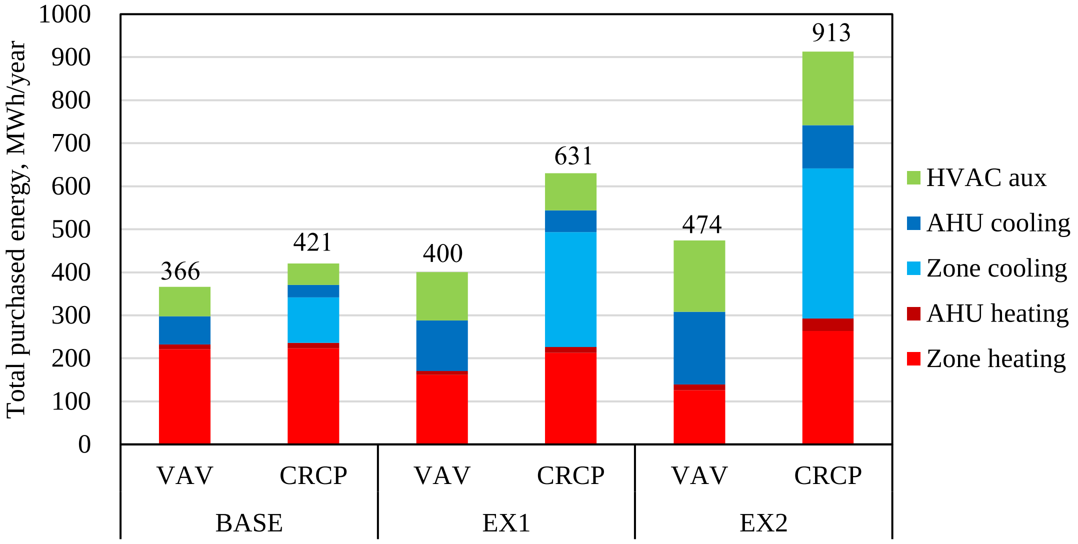


Figure 19 Total purchased heating, cooling and AHU auxiliary energy of cases EX1 and EX2, compared with BASE.

Figure 20 shows the annual energy and power costs of two systems for cases with different external loads, where heating, cooling and electricity costs are marked in red, blue and green respectively as the same with BASE. The cost of power consists of a fixed price and a variable price determined by the peak power.

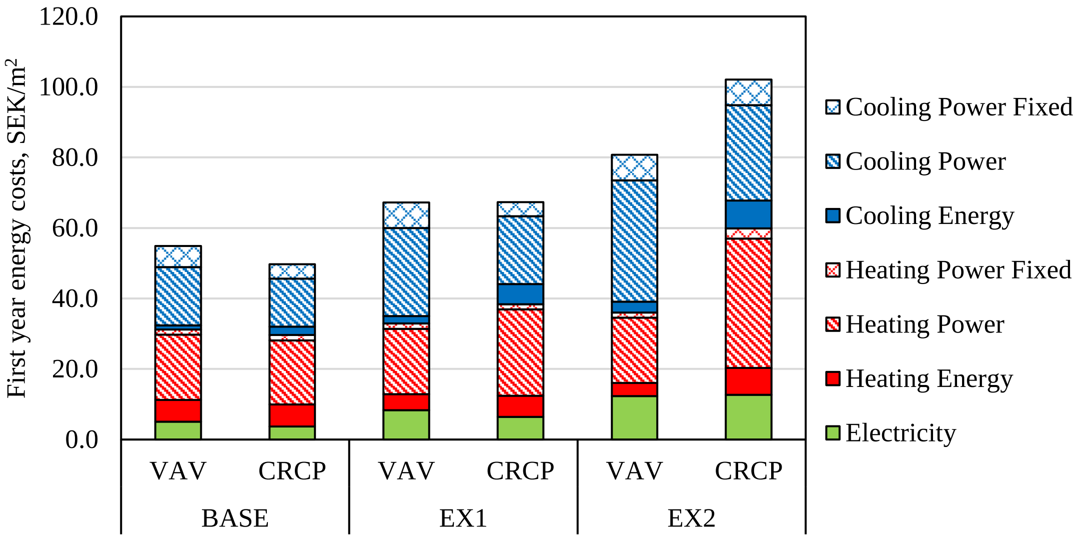


Figure 20 Annual total energy costs of case EX1 and EX2, Preset Value.

Overall, as external loads increase, both VAV and CRCP system show a rise in total annual energy costs, mainly due to higher cooling costs. Unlike BASE case, the total energy cost of CRCP system is higher in case EX1 and EX2 compared to VAV system. In more detail, while the cooling costs of both systems exhibit a similar trend to the overall energy costs, a difference occurs in their heating costs: whereas VAV experiences a decrease, CRCP sees an increase. Moreover, although the CRCP system does offer savings in cooling costs due to its lower cooling power, it requires higher heating costs. This difference is especially seen in the EX2 case, where CRCP's heating cost is nearly double that of VAV's.

In term of LCC, initial investment is the primary cost for both VAV and CRCP system in all scenarios, as shown in Figure 21. Following closely behind are maintenance and power costs, which constitute the secondary costs. The energy costs play a minimal role in total LCC in all cases.

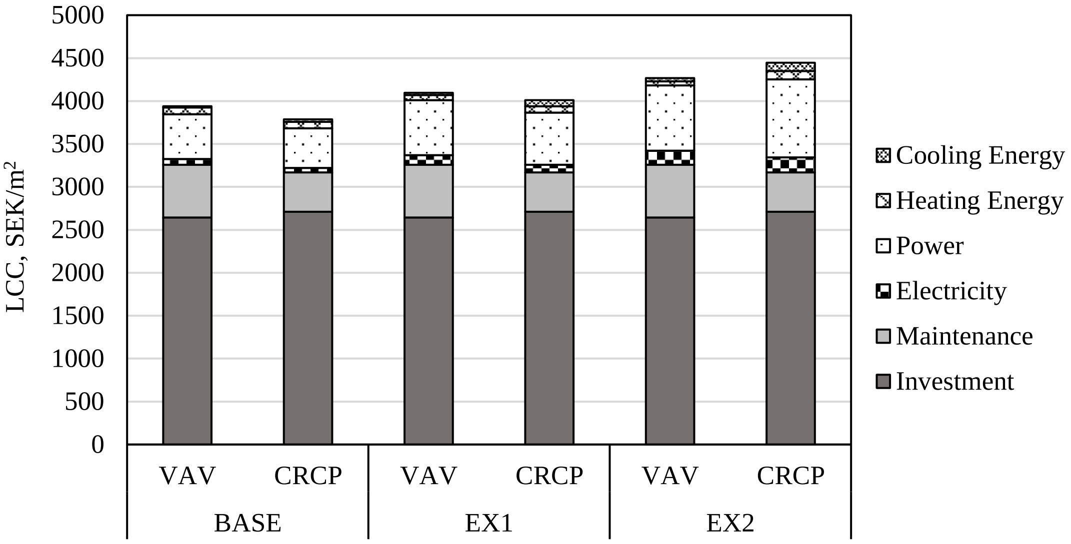


Figure 21 The LCC results of case EX1 and EX2, compared between VAV system and CRCP system.

The CRCP system shows cost saving advantages in case EX1 compared to the VAV system, but its potential benefits are lower than the BASE case. Furthermore, in the EX2 case, the LCC of CRCP system surpasses that of the VAV system due to its high operational costs, meaning that it is not an economically alternative under this condition.

4.3 Results under future Climate conditions

This section focuses on the results on the performance of VAV and CRCP system under future climate conditions, covering energy consumption, life cycle costs and thermal comfort analysis.

4.3.1 Future building demands

The Figure 22 and Figure 23 present the predicted changes in heating and cooling demands from the current to the future (year 2040). The peak power demands shown in Figure 22 were simulated using EWY and ECY weather sets and the energy demand in Figure 23 was simulated based on TDY weather data.

As expected, the heating demand shows a decrease while the cooling demand exhibits a significant increase for both peak power and energy due to rising global temperature. This reduces the need for heating during colder months while increases the need for cooling during warmer months. Especially, the annual heating energy demand becomes only half while the annual cooling energy demand will double by 2040.

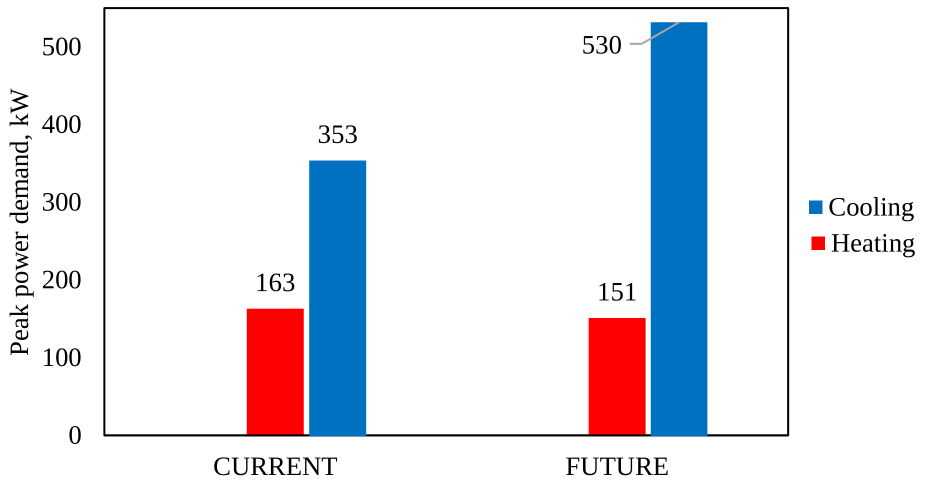


Figure 22 Peak power demand of the case building in the future.

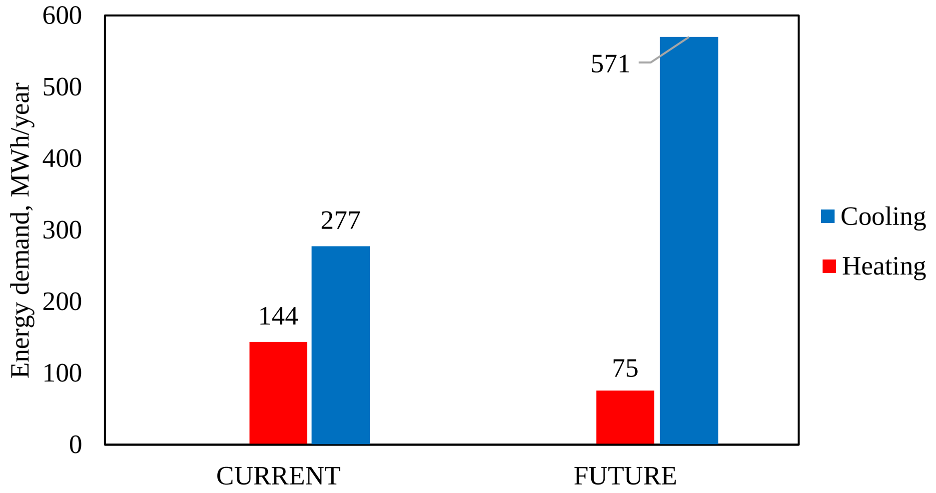


Figure 23 Heating and cooling energy demand of the case building in the future.

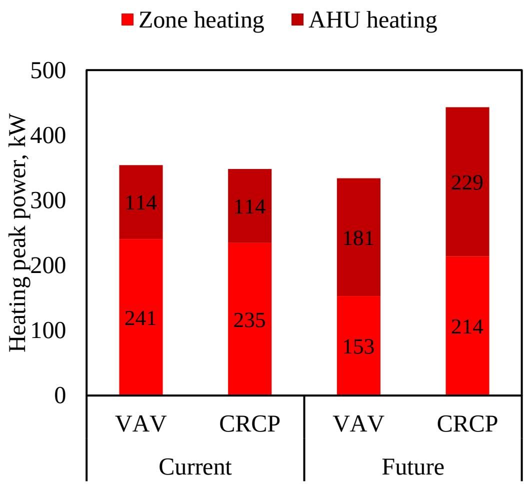
4.3.2 Future energy analysis of VAV and CRCP system

As previously mentioned in section 2.6, to address future extreme conditions, the cooling power demand results between using EWY and TDY files, the heating power demand results between using ECY and TDY files were compared. The results, displayed in Table 10, indicate that under extreme warm condition, the cooling peak power increases by approximately 30% compared to the future typical condition for both VAV and CRCP system. Similarly, the heating peak power shows an even higher increase under extreme cold condition in the future climate scenarios. The highlighted values represent the final identified peak power demands for the two systems.

Table 10 The heating and cooling power demands of the VAV and CRCP system under future climate, comparing between using TDY weather set and EWY. EXY weather sets.

	VAV			CRCP		
	EWY	**ECY**	**TDY**	**EWY**	**ECY**	**TDY**
Cooling power demand, kW	1028		786	803		634
Heating power demand, kW		334	223		443	261

The cooling power demand includes contributions from both the AHU and zone units, and the same applies to the heating power demand. Figure 24 illustrates both the heating peak power and cooling peak power for the VAV and CRCP systems, comparing current and future scenarios.



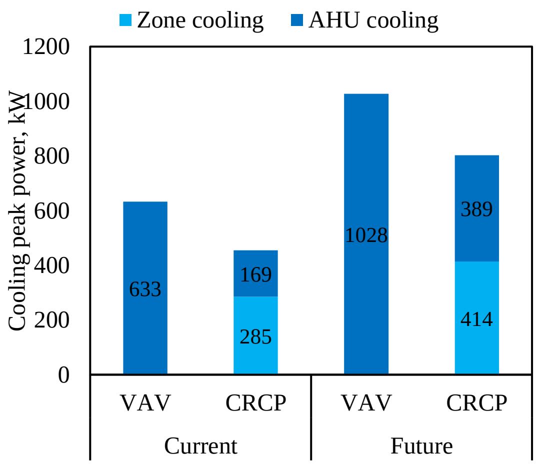


Figure 24 Heating and cooling peak power of VAV and CRCP system under future climate conditions.

The heating peak power indicates a slightly decrease in the VAV system in the future scenario due to the building's heating demand decreases due to the climate change. However, in the future scenario, the CRCP system requires lower zone heating peak power but much higher AHU heating peak power, result in higher overall heating peak power compared to the current condition. It is because the cooling capacity of panels cannot fully satisfy all the sensible cooling load due to limited available ceiling area. Consequently, the constant airflow rate of AHU becomes higher than VAV's, leading to higher reheat energy during winter.

The cooling peak power rises for both systems in the future scenario due to higher cooling demand as the future rising temperature. Moreover, in future scenario, the proportion of peak power consumed by AHU cooling becomes larger due to the need of compensated airflow, which is not needed in the current scenario.

As same as chapter 4.1, district heating, district cooling and AHU auxiliary electricity consist of total purchased energy. Overall, similar to the BASE case, the total purchased energy of CRCP system is higher than that of VAV system but the difference between two systems become more obvious, which can be seen in Figure 25. Furthermore, the purchased energy for heating decreases while it for cooling and HVAC operational electricity increases in both systems, which is as expected due to the predicted rising global temperature in the future.

It is notable that the total annual purchased energy of CRCP system increases while it decreases using VAV system in the future. It is because future rising outdoor temperature leads to an increase in cooling energy for VAV system but it is offset by a larger decrease in heating energy resulting in a slight decrease in total energy consumption.

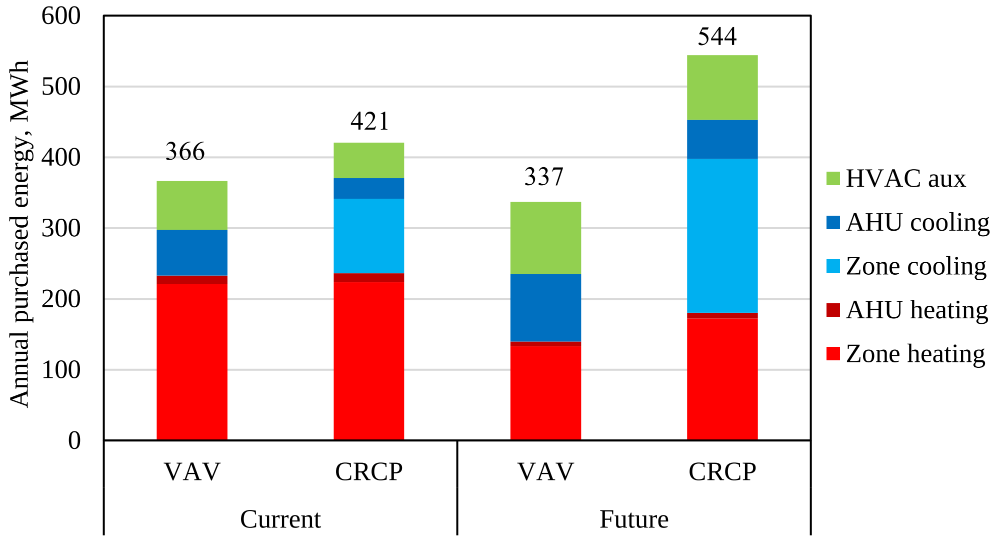


Figure 25 Annual total purchased energy of VAV and CRCP systems under future climate conditions.

Comparing the results between two systems under future climate condition, heating energy for CRCP system becomes 39 MWh/year higher than VAV system, which is because compensated airflow leads CRCP system has higher constant airflow rate during winter, and higher airflow rate causes more frequent air exchanges, thereby raising the energy consumption in both AHU heating and zone heating.

Similar to the BASE case under current climate conditions, lower airflow leads a lower AHU cooling energy for CRCP system, and therefore lower AHU auxiliary energy. However, the CRCP system requires much higher total purchased cooling energy compared to the VAV system, with more obvious difference from 107% to 186%. Due to the need for constant temperature chilled water, the CRCP system cannot use free cooling without considering other efficient cold sources such as soil, rivers, etc. On the contrary, the VAV system can take advantage of free cooling though the temperature rises in the future and causing free cooling potential decreases.

4.3.3 Future life cycle cost

As can be seen in Figure 26, the annual energy costs rise in the future for both systems. Notably, the VAV system shows a great increase in cooling power costs. Although its total energy use decreases, resulting in reduced heating costs, which leads to only a slight overall increase in total annual energy costs.

The CRCP system cannot save money in annual energy costs anymore with 2.5 SEK/m^2 higher compared to the VAV system under future climate conditions. It is mainly attributed to higher heating power and more than double the cooling energy required in CRCP system, causing more costs in the future scenario, thus offset the cost savings in cooling power and electricity.

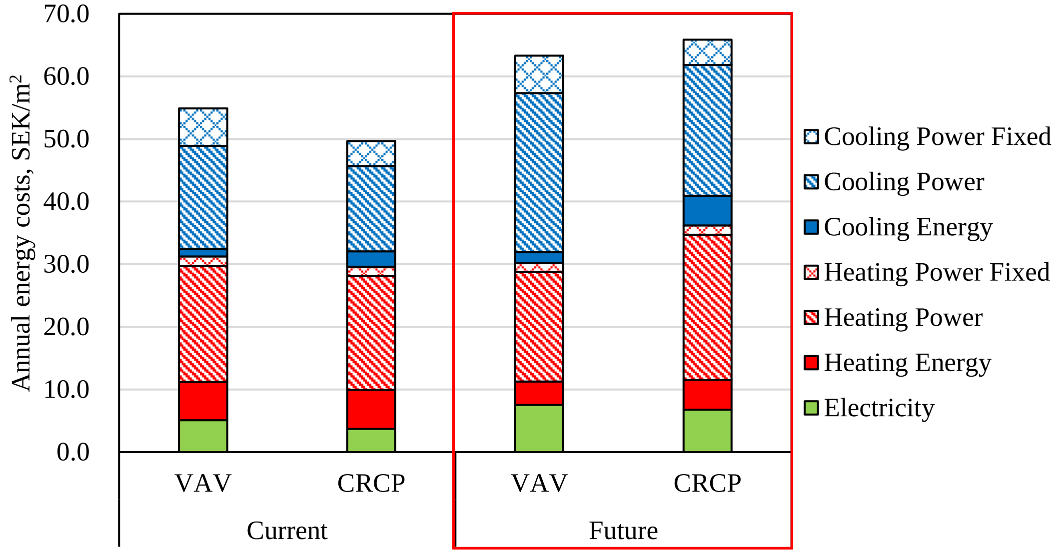


Figure 26 Annual total energy costs under future climate condition

Considering 20 years operation period, the LCC results of the future condition are presented in Figure 27. The majority of LCC remains initial investment, followed by the maintenance cost and power cost.

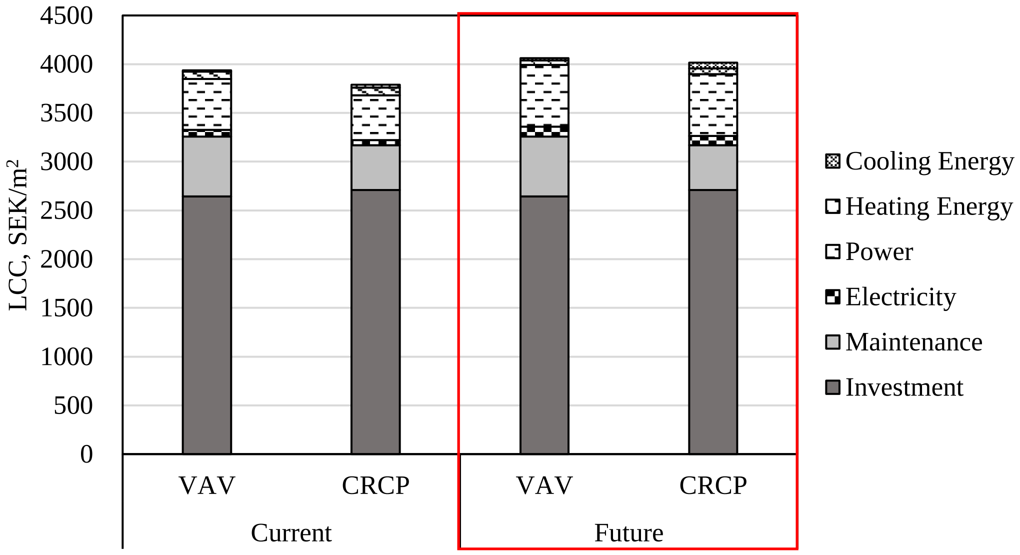


Figure 27 The LCC results under future climate condition.

Due to slightly higher annual energy costs offset the savings in maintenance costs, the cost benefit of CRCP system decreases from 150 SEK/m^2 currently to 46 SEK/m^2 in the future during 20 years calculated period.

4.3.4 Future thermal comfort

Figure 28 and Figure 29 illustrate the temperature of typical southern and eastern zones with VAV and CRCP system under future typical and extreme warm climate conditions respectively, with air temperature in dashed lines and operative temperature in solid lines.

In all scenarios and for both systems, the room air temperature consistently remains at 24 °C by using air temperature sensors, remaining lower than the operative temperature throughout the occupied hours 08-18. Regarding operative temperature, it fluctuates throughout the working hours due to variations of solar radiation. Like the BASE scenario, in future typical climate scenario, the operative temperature in CRCP system remains around 0.4 °C lower than in VAV system for both zones, which is achieved by direct heat exchange between cool surface and occupants and the lower mean radiant temperature.

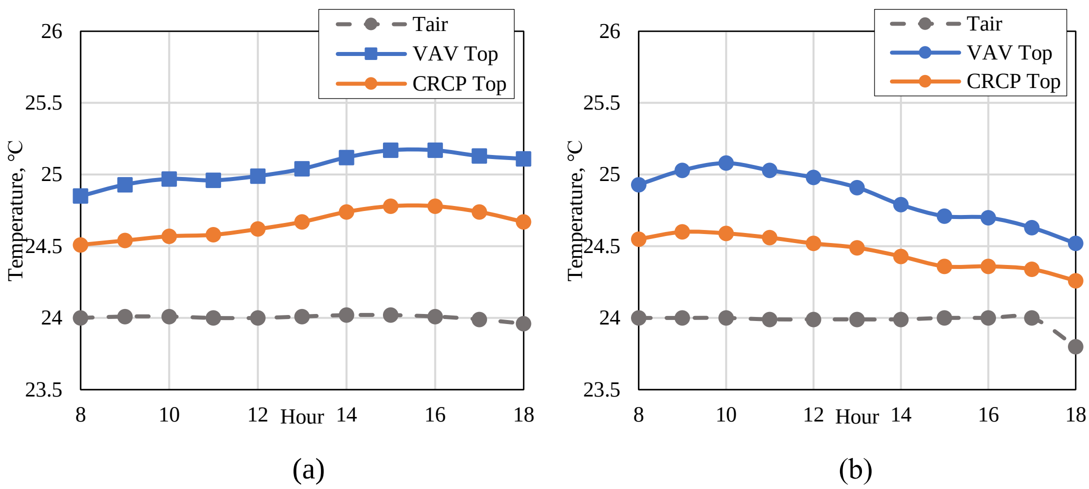


Figure 28 Air temperature and operative temperature of VAV and CRCP systems at the critical design day during occupied hours 08-18 under future typical climate condition (TDY). Two different typical zones with different orientation are analyzed: (a) South; (b)East.

Besides TDY condition, the average temperature of the 'critical week', the hottest days of the year, under future extreme warm condition is shown in Figure 29. The air temperature of the zones remains at 24 °C, validating the sizing is correct. Compared with Figure 28, it could be seen a higher and more fluctuated operative temperature in the zone facing east for both two systems, which is because extreme high temperature yields more excess heat, raising the mean radiant temperature thus the operative temperature. In addition, during an extreme warm day, the temperature difference between the radiative cooling ceiling and the external environment decreases, and the efficiency of radiative cooling decreases, causing the operating temperature to rise and change more. Like results in the current scenario, the operative temperature in the CRCP system remains lower and more stable than in the VAV, indicating that the CRCP system can provides better thermal comfort.

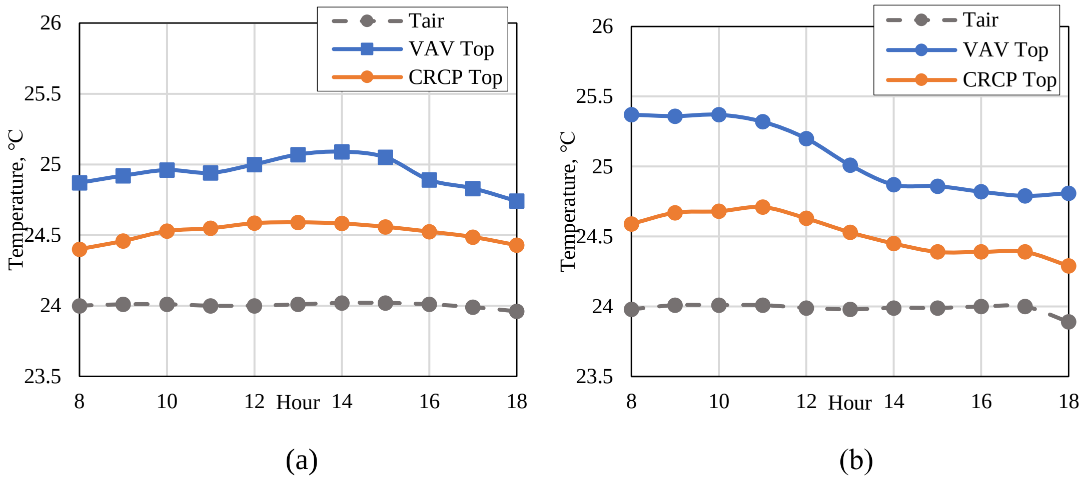


Figure 29 Air temperature and operative temperature of VAV and CRCP systems at the critical design day during occupied hours 08-18 under future extreme warm climate condition (EWY). Two different typical zones with different orientation are analyzed: (a) South; (b)East.

By using CBE Thermal Comfort Tool, the following Figure 30 presents the evaluation of the warmest hour, which occurs at eastern zone at 10 a.m., the point was seen within the comfort boundaries (blue part) in the psychrometric charts, meaning the indoor condition of all zones complies with ASHRAE Standard 55-2023 for both systems in the future scenario as well. The occupants experience a neutral thermal sensation within the zones in all scenarios.

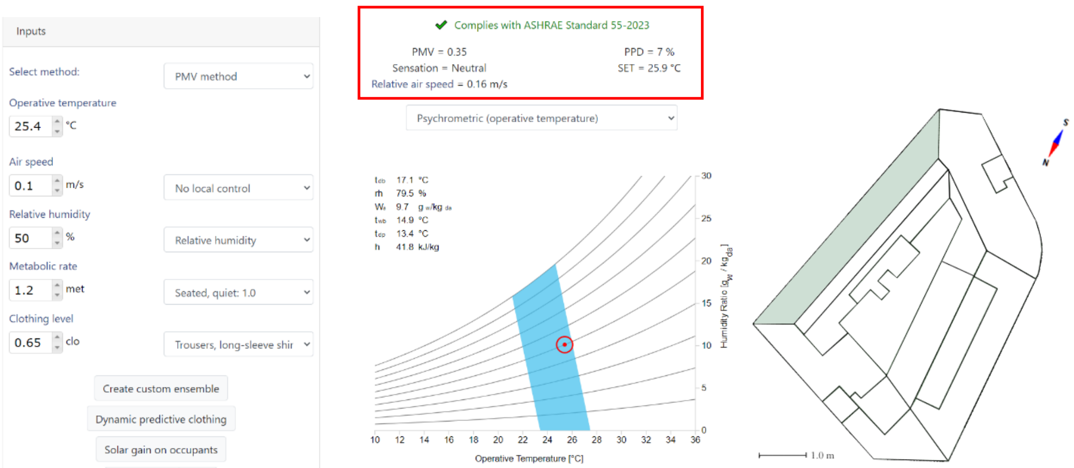


Figure 30 Thermal comfort results for the warmest condition in the future climate scenarios by using CBE Thermal Comfort Tool.

4.4 Sensitivity analysis

Sensitivity analysis of LCC is essential for the evaluation of systems' cost efficiency due to uncertainties induced by variations in affecting parameters. In this work, the sensitivity analysis focused on how fluctuation in the discount rate affects the LCC results of the systems as LCC heavily depends on it so that its impact on LCC can be significant. In Figure 12 in section 4.1 and 4.4, the LCC results were calculated using the current discount rate of 6%. However, such results may not be accurate in the future as the discount rate changes, especially over a long service period.

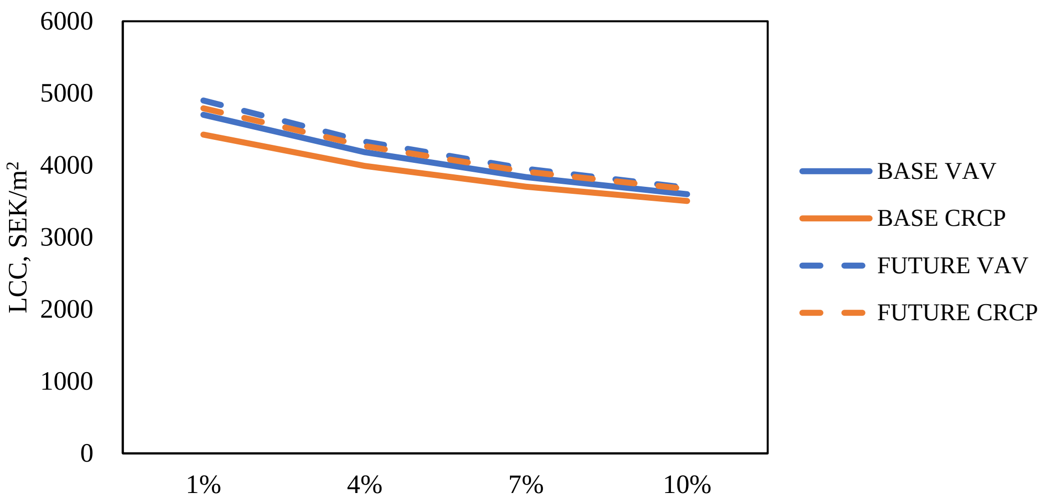


Figure 31 The LCC results of VAV and CRCP system with the discount rate 1% to 10%.

Figure 31 shows the LCC results of VAV and CRCP system with the discount rate ranging from 1% to 10% under both current and future climate conditions. Overall, a decrease trend can be seen for both VAV and CRCP systems in LCC as the discount rate increases across the range of 1% to 10%. VAV system always exhibits a higher life cycle cost compared to CRCP system. At a discount rate of 1%, the LCC difference of two systems reach 275 SEK/m^2 in total. However, Figure 31 suggests a diminishing distinction between two systems as the discount rate rises, where the difference in LCC reduces to just 94 SEK/m^2 at the discount rate of 10%, approximate 1/3 of that at 1%. In the future scenarios, the LCC shows a similar trend to that observed in the current scenarios.

The results highlight that the cost differentials are highly sensitive to variation in the discount rate. As the discount rate increases, the economic advantage of alternative solution CRCP system decreases, which may lead to a narrowing of the gap in their attractiveness.

5 Discussion

This chapter discusses the findings and underlying reasons, as well as addressed limitations and future research suggestions.

Energy performance

The total purchased energy of the CRCP system is higher than VAV system in all considered scenarios, especially, it consumes much higher cooling energy. This result is contrary to some literatures where they believe the CRCP system can save energy and savings are argued to stem from the decoupled ventilation, peak power reduction and higher thermal efficiency. Although, the energy savings achieved in part have been validated through the results of this study such as savings in peak power demand and HVAC auxiliary electricity, it is ascertained that the CRCP system always consume higher cooling energy than the VAV system.

In addition, CRCP system, a water-based radiant cooling system, has two disadvantages: it cannot deal with the latent loads and has limited cooling capacity. These factors are very important in the design and operation of the system, which is also emphasized by the current literature that it is essential to avoid condensation and integrate the system with a DOAS. In this study, while there is no risk of condensation, the limited cooling capacity of panels still affects the design and energy performance of the CRCP system. For example, in the EX2 case, the cooling capacity of the panels using maximum ceiling area fail to meet the zone temperature setpoint, so compensated airflow is needs, and thus highly increased the energy consumption.

Moreover, this study did not consider the influence of heat sources. The integration of high-efficiency heat sources, such as ground source heat pumps, could significantly impact the performance and total purchased energy of the CRCP system. Ground source heat pumps can provide free cooling by leveraging the stable temperatures of the ground, reducing the reliance on traditional refrigeration systems. In addition, the CRCP system can operate with high temperature cooling water (>16°C) which is compatible with some sources like boreholes. Previous studies have implemented the boreholes in active chilled beams systems, validating the potential for energy savings[41], [42]. Since the active chilled beams system is another water-based radiant system, it is reasonable to expect that integrating boreholes with the CRCP system could offer even greater potential for energy savings.

Additionally, other renewable energy sources, such as solar thermal systems and photovoltaic (PV) panels, could be considered to further reduce the operational costs of both the VAV and CRCP systems. Solar thermal systems can supply heating or cooling, and PV panels can offset the HVAC auxiliary electricity, contributing to better energy efficiency.

It is also important to note that the operational period of cooling systems is often longer in reality than what simulations, further increasing the total energy use for both systems.

Life cycle cost performance

The majority of LCC is initial investment, accounting for approximately 70% of the total LCC over 20 years. The maintenance costs and power costs play the secondary attributions.

The LCC of CRCP system is lower than VAV system in most scenarios, except the case EX2. The primary factor contributing to this is the reduced maintenance costs and operational costs associated with lower peak power, despite the higher investment costs and higher energy costs. The lower LCC suggests that, the CRCP system is cost-efficient from a long-term financial perspective.

However, in case EX2 scenario, extreme high solar heat gain through windows leads extreme high compensation airflow for CRCP system, resulting in almost double the heating peak power and the total purchased energy. Therefore, the LCC savings in cooling peak power reduction is lower than increasing in heating peak power, leading to a non-profit LCC.

Performances under future climate conditions

As global temperatures rise, the cooling demand is expected to increase significantly. The CRCP system, with its lower cooling peak power demand, is likely to be more resilient to rising temperatures, offering better energy efficiency and cost savings in the long term. However, its dependence on continuous chilled water circulation, resulting in significantly higher purchased energy, may become a disadvantage if the cooling demand surpasses its capacity, especially in conditions experiencing extreme heatwaves. Consequently, the cost efficiency of the CRCP system will decrease due to the substantially higher purchased energy and thereby the attractiveness of the CRCP system will decrease.

Limitations

The findings of this study are specific to Sweden's climate conditions. Results may vary significantly in different geographic locations with different climate profiles. Sweden has oceanic climate, with characterized by cold winters and mild summers. In regions with similar climates, the CRCP and VAV systems may exhibit comparable behavior. For example, with mild summers, the dew point is relatively low, allowing chilled water temperatures to be maintained at 16°C without the risk of condensation. However, in regions with warm and humid climate conditions, where the dew point is high and the risk of condensation is elevated, the performance of these systems could differ substantially. In such climates, the high humidity levels can increase latent loads, which the CRCP system is not able to handle. This can lead to issues with condensation and increase the airflow needed for dehumidification, and thus potentially increasing operational costs. Furthermore, a high dew point increases the minimum allowed chilled water temperature, thereby decrease the cooling capacity of panels per unit area. Consequently, the CRCP system's limited cooling capacity may struggle to meet the higher cooling demands, leading to reduced effectiveness and increased reliance on compensated airflow.

Furthermore, the cost analysis is simplified: the investment cost was calculated by using experience value per floor area, and the annual maintenance cost were calculated as a percentage of the investment cost. This simplified method is applied due to the lack of the CRCP system in practice and lack of experience in Sweden. Under this method, the changes such as ducts sizing, AHU sizing and pipes sizing were not accounting detailed, and thus the cost variations associated with different designs in parametric study and under different climate conditions are not reflected.

Future research

For future research, it would be great to investigate the following:

1) Integration of Alternative Heat Sources: Study the impact of integrating alternative heat sources, such as ground source heat pumps or renewable energy systems (e.g. PV panels), on the energy and cost performance of both VAV and CRCP systems.

2) Chilled Water Temperature: Examine the impact of chilled water temperature on the design and performance of the CRCP system.

3) Part Load Conditions: Take into account part load conditions which is more realistic to understand their effect on system performance.

4) Detailed Cost Estimates: Provide more detailed cost estimates, such as the costs of diffusers, panels, ductwork and other component. With more detailed cost estimates, the initial investment for two systems will vary across different scenarios. For example, in the future scenario, with high cooling demand, the investment will be higher due to the need for more panels, larger ducts and pipes, and a larger AHU compared to the current scenario.

6 Conclusion

This study comprehensively compared the variable air volume (VAV) system and ceiling radiant cooling panels (CRCP) system in terms of peak power demand, total purchased energy, life cycle cost, and thermal comfort for a case building located in Gothenburg under current and future climate conditions. It answered the research questions purposed in chapter 1.3.

What are the purchased energy and peak power demand differences between VAV system and ceiling cooling panel system?

The CRCP system has a higher purchased energy compared to the VAV system due to the continuous low temperature chilled water required to maintain indoor conditions.

On the other hand, though CRCP system requires the identical heating peak power as VAV system, it demonstrates a much lower cooling peak power demand compared to the VAV system, especially AHU peak power is below 30% of VAV's due to significantly lower airflow. It can be explained based on the heat removal mechanisms of two systems: CRCP system removes heat by radiation and convection while VAV system removes heat solely be convection.

What the life cycle cost differences between VAV system and ceiling cooling panel system?

The investment is the major part of the LCC for both two systems, where the CRCP system cost 65 SEK/m^2 higher than VAV system. However, it saves approximately 40 SEK/m^2 maintenance cost per year, and its savings becomes more obvious over time.

Regarding energy costs in LCC, the power cost stands essential. The CRCP system shows lower total operational cost than VAV system, which attributes to lower peak power. The savings associated with lower peak power overweigh the slightly higher purchased energy cost. As a result, the CRCP system has a lower LCC, indicating better financial efficiency over twenty years.

How does internal loads and external loads affect the energy performances of the building?

As internal and external loads increase, the heating peak power remains constant while the cooling peak power increases in the VAV system due to the peak load calculation methods. In the CRCP system, increasing airflow caused by limited ceiling area leads to an increase in both heating and cooling peak power. Moreover, the CRCP system exhibits a significant lower cooling peak power in all cases, but it requires higher heating peak power when compensated airflow is needed. This can be explained by constant higher airflow ventilation during winter, enhancing the heat exchange within warm and cool air and thus increase the need of reheat.

The impact of internal and external loads of the energy performance is different for two systems. Increasing internal and external loads both lead to higher purchased cooling energy for both systems due to more excess heat needs to be removed. With high internal loads, the VAV system needs more energy in heating coil due to higher airflow due to need of cooling for center zones. However, with high external loads, the heating energy consumption of the CRCP system is higher than the VAV system because high compensation airflow leads to high constant airflow in winter.

What will be the energy performances of the building under projected future climate conditions?

The projected future rising global temperature leads to a decrease in heating demand while a significant increase in cooling demand. Especially, the annual heating energy demand becomes only half while the annual cooling energy demand will double by 2040. Therefore, more than 60% higher cooling peak power are required in both two system in the future. Moreover, the CRCP system requires higher heating peak power due to high compensation airflow.

Regarding purchased energy, the CRCP system purchases both more heating and cooling energy compared to the VAV system, due to the need of high compensation airflow as well. Furthermore, the total purchased energy of VAV system decreases in the future scenario, which is because the increase in cooling energy is offset by the large decrease in heating energy.

In conclusion, the CRCP system is an effective alternative mechanical cooling system with significant potential for reducing peak power demand and providing long term cost efficiency both under current and future climate conditions.

References

[1] M. Santamouris and K. Vasilakopoulou, “Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 1, p. 100002, Jan. 2021, doi: 10.1016/j.prime.2021.100002.

[2] J. L. Niu, L. Z. Zhang, and H. G. Zuo, “Energy savings potential of chilled-ceiling combined with desiccant cooling in hot and humid climates,” *Energy and Buildings*, vol. 34, no. 5, pp. 487–495, Jun. 2002, doi: 10.1016/S0378-7788(01)00132-3.

[3] A. Inayat and M. Raza, “District cooling system via renewable energy sources: A review,” *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 360–373, Jun. 2019, doi: 10.1016/j.rser.2019.03.023.

[4] M. Santamouris, “Cooling the buildings – past, present and future,” *Energy and Buildings*, vol. 128, pp. 617–638, Sep. 2016, doi: 10.1016/j.enbuild.2016.07.034.

[5] S. Werner, “European space cooling demands,” *Energy*, vol. 110, pp. 148–156, Sep. 2016, doi: 10.1016/j.energy.2015.11.028.

[6] A. Fellegvari, “Design of Active Chilled Beam systems: Detailed economic analyses for different design temperatures and airflows,” 2023, Accessed: Apr. 29, 2024. [Online]. Available: http://hdl.handle.net/20.500.12380/306953

[7] “Variable Air Volume (VAV) Systems Operations and Maintenance.” Accessed: Mar. 31, 2024. [Online]. Available: https://www.pnnl.gov/projects/om-best-practices/variable-air-volume-systems

[8] “Dieckmann, J., Roth, K. W., & Brodrick, J. (2004). Radiant ceiling cooling. ASHRAE journal, 46, 42-42.” Accessed: Apr. 29, 2024. [Online]. Available: http://www.doas-radiant.psu.edu/Journal_Emerging_CRCP_04.pdf

[9] A. Novoselac and J. Srebric, “A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems,” *Energy and Buildings*, vol. 34, no. 5, pp. 497–509, Jun. 2002, doi: 10.1016/S0378-7788(01)00134-7.

[10] S. A. Mumma, “Ceiling Panel Cooling Systems,” *ASHRAE Journal*, 2001.

[11] F. C. McQuiston, J. D. Parker, J. D. Spitler, and H. Taherian, *Heating, Ventilating, and Air Conditioning: Analysis and Design*. John Wiley & Sons, 2023.

[12] “Overview of integrating dedicated outdoor air systems with parallel terminal systems / Discussion - ProQuest.” Accessed: Apr. 29, 2024. [Online]. Available:

https://www.proquest.com/openview/92e174c675bbc92b577dcd6340bfd8c9/1?cbl=34619&pq-origsite=gscholar

[13] J. Miriel, L. Serres, and A. Trombe, “Radiant ceiling panel heating–cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumptions,” *Applied Thermal Engineering*, vol. 22, no. 16, pp. 1861–1873, Nov. 2002, doi: 10.1016/S1359-4311(02)00087-X.

[14] L. Bergia Boccardo, O. B. Kazanci, J. Quesada Allerhand, and B. W. Olesen, “Economic comparison of TABS, PCM ceiling panels and all-air systems for cooling offices,” *Energy and Buildings*, vol. 205, p. 109527, Dec. 2019, doi: 10.1016/j.enbuild.2019.109527.

[15] T. Imanari, T. Omori, and K. Bogaki, “Thermal comfort and energy consumption of the radiant ceiling panel system.: Comparison with the conventional all-air system,” *Energy and Buildings*, vol. 30, no. 2, pp. 167–175, Jun. 1999, doi: 10.1016/S0378-7788(98)00084-X.

[16] S. A. Mumma, “Chilled Ceiling Condensation Control”.

[17] P. Simmonds, “The utilization and optimization of a building’s thermal inertia in minimizing the overall energy use,” *ASHRAE Transactions*, vol. 97, pp. 1031–1042, Jan. 1991.

[18] M. Amini, R. Maddahian, and S. Saemi, “Numerical investigation of a new method to control the condensation problem in ceiling radiant cooling panels,” *Journal of Building Engineering*, vol. 32, p. 101707, Nov. 2020, doi: 10.1016/j.jobe.2020.101707.

[19] W. Jin, L. Jia, and P. Gao, “Study of a condensation-prevention method based on water supply regulation for a radiant ceiling cooling system,” *Science and Technology for the Built Environment*, vol. 23, no. 2, pp. 229–240, Feb. 2017, doi: 10.1080/23744731.2016.1260411.

[20] W. Liao, J. Peng, Y. Luo, Y. He, N. Li, and Y. A, “Comparative study on energy consumption and indoor thermal environment between convective air-conditioning terminals and radiant ceiling terminals,” *Building and Environment*, vol. 209, p. 108661, Feb. 2022, doi: 10.1016/j.buildenv.2021.108661.

[21] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, “World Map of the Köppen-Geiger climate classification updated,” *metz*, vol. 15, no. 3, pp. 259–263, Jul. 2006, doi: 10.1127/0941-2948/2006/0130.

[22] P. Sahlin, “IDA ICE Getting Started”.

[23] K. Hilliaho, J. Lahdensivu, and J. Vinha, “Glazed space thermal simulation with IDA-ICE 4.61 software—Suitability analysis with case study,” *Energy and Buildings*, vol. 89, pp. 132–141, Feb. 2015, doi: 10.1016/j.enbuild.2014.12.041.

[24] E. M. Ryan and T. F. Sanquist, “Validation of building energy modeling tools under idealized and realistic conditions,” *Energy and Buildings*, vol. 47, pp. 375–382, Apr. 2012, doi: 10.1016/j.enbuild.2011.12.020.

[25] A. Hesaraki and S. Holmberg, “Demand-controlled ventilation in new residential buildings: Consequences on indoor air quality and energy savings,” *Indoor and Built Environment*, vol. 24, no. 2, pp. 162–173, Apr. 2015, doi: 10.1177/1420326X13508565.

[26] “BBR 2011- the Swedish building regulations.”

[27] “Cooling and Heating Equations.” Accessed: Apr. 29, 2024. [Online]. Available: https://www.engineeringtoolbox.com/cooling-heating-equations-d_747.html

[28] “2021 ASHRAE handbook.”

[29] “Water - Heat of Vaporization vs. Temperature.” Accessed: Apr. 09, 2024. [Online]. Available: https://www.engineeringtoolbox.com/water-properties-d_1573.html?vA=21&units=C#

[30] “AQUATHERM BLACK technical catalogue.” Accessed: Apr. 10, 2024. [Online]. Available: https://www.aquatherm.de/fileadmin/user_upload/Germany/Downloads/Kataloge/aquatherm_black_system_9900000045.pdf

[31] J. Y. Park and Z. Nagy, “Comprehensive analysis of the relationship between thermal comfort and building control research - A data-driven literature review,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2664–2679, Feb. 2018, doi: 10.1016/j.rser.2017.09.102.

[32] “Tools,” Center for the Built Environment. Accessed: May 01, 2024. [Online]. Available: https://cbe.berkeley.edu/resources/tools/

[33] “CBE Thermal Comfort Tool.” Accessed: May 01, 2024. [Online]. Available: https://comfort.cbe.berkeley.edu

[34] J. Ngarambe, G. Y. Yun, and G. Kim, “Prediction of indoor clothing insulation levels: A deep learning approach,” *Energy and Buildings*, vol. 202, p. 109402, Nov. 2019, doi: 10.1016/j.enbuild.2019.109402.

[35] V. M. Nik, “Making energy simulation easier for future climate – Synthesizing typical and extreme weather data sets out of regional climate models (RCMs),” *Applied Energy*, vol. 177, pp. 204–226, Sep. 2016, doi: 10.1016/j.apenergy.2016.05.107.

[36] A. Moazami, V. M. Nik, S. Carlucci, and S. Geving, “Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions,” *Applied Energy*, vol. 238, pp. 696–720, Mar.

2019, doi: 10.1016/j.apenergy.2019.01.085.

[37] M. Spickova and R. Myskova, "Costs Efficiency Evaluation using Life Cycle Costing as Strategic Method," *Procedia Economics and Finance*, vol. 34, pp. 337–343, Jan. 2015, doi: 10.1016/S2212-5671(15)01638-X.

[38] J. Schade, "LIFE CYCLE COST CALCULATION MODELS FOR BUILDINGS".

[39] M. Kishk, A. Al-Hajj, R. Pollock, G. Aouad, N. Bakis, and M. Sun, "Whole life costing in construction: a state of the art review.," Dec. 2003, Accessed: Apr. 23, 2024. [Online]. Available: https://rgu-repository.worktribe.com/output/248559

[40] "Göteborg Energi," Göteborg Energi. Accessed: Apr. 19, 2024. [Online]. Available: https://www.goteborgenergi.se/

[41] T. Arghand, S. Javed, A. Trüschel, and J.-O. Dalenbäck, "A comparative study on borehole heat exchanger size for direct ground coupled cooling systems using active chilled beams and TABS," *Energy and Buildings*, vol. 240, p. 110874, Jun. 2021, doi: 10.1016/j.enbuild.2021.110874.

[42] "Direct Ground Cooling Systems for Office Buildings - ProQuest." Accessed: Jun. 18, 2024. [Online]. Available: https://www.proquest.com/openview/86e44157896eacde8fa2cb9372a06a0d/1?pq-origsite=gscholar&cbl=2026366&diss=y

Appendix A

	BASE			EX1			EX2		
Zone	Actual panel number, st	Compensated airflow, L/s	Total airflow, L/s	Actual panel number, st	Compensated airflow, L/s	Total airflow, L/s	Actual panel number, st	Compensated airflow, L/s	Total airflow, L/s
0_Fläktrum	0	0	24.4	0	0.0	24.4	0	0.0	24.4
0_Garage	0	0	563.2	0	0.0	563.2	0	0.0	563.2
0_Inlastning/Miljörum	0	0	28.0	0	0.0	28.0	0	0.0	28.0
0_UC	0	0	64.8	0	0.0	64.8	0	0.0	64.8
1_Gym	135	0	751.6	240	0.0	751.6	276	1501.8	2253.3
1_Lokal 1	55	0	452.1	114	0.0	452.1	168	0.0	452.1
1_Restaurant	38	0	356.8	83	0.0	356.8	131	0.0	356.8
2_Cellkontor mot gård	10	0	138.9	12	0.0	138.9	13	0.0	138.9
2_Landskap	51	0	251.9	97	33.3	285.1	97	1045.9	1297.8
2_Landskap1	49	0	241.4	93	7.5	248.9	93	655.0	896.4
2_Landskap3	67	0	230.2	89	1008.0	1238.1	89	2542.2	2772.4
2_Landskap4	10	0	91.7	18	0.0	91.7	26	0.0	91.7
2_Landskap5	12	0	141.1	19	0.0	141.1	31	0.0	141.1
2_Övrigt	2	0	56.1	2	0.0	56.1	3	0.0	56.1
2_Övrigt2	3	0	93.6	4	0.0	93.6	5	0.0	93.6
2_Pausyta	1	0	89.8	2	0.0	89.8	3	0.0	89.8
2_Pausyta1	0	0	41.5	0	0.0	41.5	1	0.0	41.5
2_Pausyta2	0	0	42.4	1	0.0	42.4	2	0.0	42.4
3_Cellkontor mot gård	10	0	139.2	10	0.0	139.2	10	0.0	139.2

3_Landskap	47	0	241.4	87	0.0	241.4	93	490.2	731.6
3_Landskap6	65	0	230.2	89	880.3	1110.5	89	2326.1	2556.2
3_Landskap7	13	0	141.2	19	0.0	141.2	28	0.0	141.2
3_Landskap8	47	0	211.6	81	167.2	378.8	81	1089.1	1300.7
3_Landskap9	10	0	91.7	15	0.0	91.7	24	0.0	91.7
3_Övrigt	3	0	99.8	3	0.0	99.8	4	0.0	99.8
3_Övrigt3	3	0	93.6	4	0.0	93.6	4	0.0	93.6
3_Pausyta3	0	0	43.6	0	0.0	43.6	0	0.0	43.6
3_Pausyta4	0	0	89.8	1	0.0	89.8	1	0.0	89.8
3_Pausyta5	0	0	41.5	0	0.0	41.5	0	0.0	41.5
4 Ljusgård	0	0	140.3	0	0.0	140.3	0	0.0	140.3
4_Cellkontor mot gård	2	0	24.8	2	0.0	24.8	2	0.0	24.8
5_Landskap14	49	0	246.6	92	0.0	246.6	95	858.6	1105.3
5_Pausyta5	0	0	46.0	1	0.0	46.0	1	0.0	46.0
6 Ljusgård	5	0	140.1	13	0.0	140.1	22	0.0	140.1
6_Landskap20	50	0	251.6	94	0.0	251.6	97	882.4	1134.0
6_Pausyta11	0	0	104.2	1	0.0	104.2	1	0.0	104.2
7 Ljusgård	0	0	140.0	0	0.0	140.0	0	0.0	140.0
7_Landskap	48	0	260.2	88	0.0	260.2	100	343.1	603.3
7_Landskap23	51	0	251.8	96	0.0	251.8	97	926.1	1177.9
8_Landskap	59	0	170.8	66	1029.0	1199.7	66	1862.3	2033.1
8_Landskap26	15	0	139.8	21	0.0	139.8	28	0.0	139.8
8_Landskap27	81	0	230.2	89	1581.8	1812.0	89	2990.5	3220.7
8_Landskap28	63	0	251.6	97	491.1	742.7	97	1747.9	1999.5
8_Landskap29	12	0	94.1	19	0.0	94.1	26	0.0	94.1
8_Övrigt5	3	0	99.2	4	0.0	99.2	4	0.0	99.2
8_Övrigt8	4	0	93.6	5	0.0	93.6	5	0.0	93.6

8_Pausyta8	2	0	78.3	3	0.0	78.3	3	0.0	78.3
8_Pausyta14	2	0	89.8	3	0.0	89.8	3	0.0	89.8
8_Pausyta15	0	0	43.4	1	0.0	43.4	1	0.0	43.4
9_Fläktrum	0	0	128.0	0	0.0	128.0	0	0.0	128.0
9_Fläktrum2	0	0	120.6	0	0.0	120.6	0	0.0	120.6
9_Passage	0	0	37.3	0	0.0	37.3	0	0.0	37.3
Ljusgård_	0	0	83.7	0	0.0	83.7	3	0.0	83.7
TH_1	0	0	7.1	0	0.0	7.1	0	0.0	7.1
TH_2	0	0	68.6	0	0.0	68.6	0	0.0	68.6
TH_3	0	0	60.5	0	0.0	60.5	0	0.0	60.5
TH_4	0	0	134.0	0	0.0	134.0	0	0.0	134.0
TH_5	0	0	38.2	0	0.0	38.2	0	0.0	38.2

	IN1			**IN2**			**FUTURE**		
Zone	**Actual panel number, st**	**Compensated airflow, L/s**	**Total airflow, L/s**	**Actual panel number, st**	**Compensated airflow, L/s**	**Total airflow, L/s**	**Actual panel number, st**	**Compensated airflow, L/s**	**Total airflow, L/s**
0_Fläktrum	0	0.0	24.4	0	0.0	24.4	0	0.0	24.4
0_Garage	0	0.0	563.2	0	0.0	563.2	0	0.0	563.2
0_Inlastning/Miljörum	0	0.0	28.0	0	0.0	28.0	0	0.0	28.0
0_UC	0	0.0	64.8	0	0.0	64.8	0	0.0	64.8
1_Gym	190	0.0	884.3	246	0.0	1016.8	261	0.0	751.6
1_Lokal 1	84	0.0	520.0	112	0.0	587.8	47	0.0	452.1
1_Restaurant	59	0.0	410.2	82	0.0	463.8	156	0.0	356.8
2_Cellkontor mot gård	20	0.0	173.5	29	0.0	191.5	11	0.0	138.9
2_Landskap	69	0.0	314.8	85	0.0	347.4	52	0.0	251.9

2_Landskap1	66	0.0	301.7	82	0.0	333.0	47	0.0	241.4
2_Landskap3	83	0.0	287.6	89	195.0	512.4	89	688.4	918.6
2_Landskap4	16	0.0	114.6	22	0.0	126.4	13	0.0	91.7
2_Landskap5	22	0.0	176.3	31	0.0	194.5	54	191.0	332.1
2_Övrigt	3	0.0	70.0	5	0.0	77.3	2	0.0	56.1
2_Övrigt2	6	0.0	117.0	8	0.0	129.1	4	0.0	93.6
2_Pausyta	3	0.0	103.3	6	0.0	116.7	9	0.0	89.8
2_Pausyta1	1	0.0	47.8	2	0.0	54.0	4	0.0	41.5
2_Pausyta2	2	0.0	48.7	3	0.0	55.1	4	0.0	42.4
3_Cellkontor mot gård	20	0.0	173.9	29	0.0	192.0	10	0.0	139.2
3_Landskap	64	0.0	301.7	80	0.0	333.0	72	0.0	241.4
3_Landskap6	81	0.0	287.6	89	157.2	474.6	89	1186.3	1416.5
3_Landskap7	23	0.0	176.5	32	0.0	194.8	54	108.0	249.3
3_Landskap8	62	0.0	264.5	76	0.0	291.9	77	0.0	211.6
3_Landskap9	17	0.0	114.6	23	0.0	126.4	35	164.5	256.2
3_Övrigt	6	0.0	124.7	8	0.0	137.6	3	0.0	99.8
3_Övrigt3	6	0.0	117.0	8	0.0	129.1	3	0.0	93.6
3_Pausyta3	0	0.0	50.2	0	0.0	56.7	3	0.0	43.6
3_Pausyta4	1	0.0	103.3	1	0.0	116.7	1	0.0	89.8
3_Pausyta5	2	0.0	47.8	2	0.0	54.0	2	0.0	41.5
4 Ljusgård	0	0.0	140.3	0	0.0	140.3	0	0.0	140.3
4_Cellkontor mot gård	4	0.0	31.0	5	0.0	34.2	2	0.0	24.8
5_Landskap14	66	0.0	308.2	82	0.0	340.1	48	0.0	246.6
5_Pausyta5	2	0.0	52.9	3	0.0	59.8	5	0.0	46.0
6 Ljusgård	7	0.0	140.1	9	0.0	140.1	4	0.0	140.1
6_Landskap20	68	0.0	314.4	85	0.0	347.0	50	0.0	251.6
6_Pausyta11	3	0.0	119.9	6	0.0	135.5	11	0.0	104.2

7 Ljusgård	0	0.0	140.0	0	0.0	140.0	0	0.0	140.0
7_Landskap	66	0.0	325.1	83	0.0	358.8	51	0.0	260.2
7_Landskap23	69	0.0	314.7	86	0.0	347.3	67	0.0	251.8
8_Landskap	66	124.2	337.6	66	368.3	603.8	57	0.0	170.8
8_Landskap26	25	0.0	174.6	35	0.0	192.8	54	213.9	353.6
8_Landskap27	89	119.2	406.8	89	442.5	759.9	89	1452.8	1683.0
8_Landskap28	82	0.0	314.4	97	35.2	382.2	62	0.0	251.6
8_Landskap29	19	0.0	117.6	25	0.0	129.8	36	21.7	115.8
8_Övrigt5	6	0.0	124.0	9	0.0	136.9	10	0.0	99.2
8_Övrigt8	7	0.0	117.0	10	0.0	129.1	8	0.0	93.6
8_Pausyta8	4	0.0	90.0	6	0.0	101.7	2	0.0	78.3
8_Pausyta14	4	0.0	103.3	7	0.0	116.7	4	0.0	89.8
8_Pausyta15	2	0.0	49.9	3	0.0	56.4	0	0.0	43.4
9_Fläktrum	0	0.0	128.0	0	0.0	128.0	0	0.0	128.0
9_Fläktrum2	0	0.0	120.6	0	0.0	120.6	0	0.0	120.6
9_Passage	2	0.0	43.5	2	0.0	49.2	2	0.0	37.3
Ljusgård_	0	0.0	83.7	2	0.0	83.7	0	0.0	83.7
TH_1	0	0.0	7.1	0	0.0	7.1	0	0.0	7.1
TH_2	0	0.0	68.6	0	0.0	68.6	0	0.0	68.6
TH_3	0	0.0	60.5	0	0.0	60.5	0	0.0	60.5
TH_4	0	0.0	134.0	0	0.0	134.0	0	0.0	134.0
TH_5	0	0.0	38.2	0	0.0	38.2	0	0.0	38.2

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services

Department of Building and Environmental Technology