

# Resiliency comparison of radiant cooling systems and all-air systems

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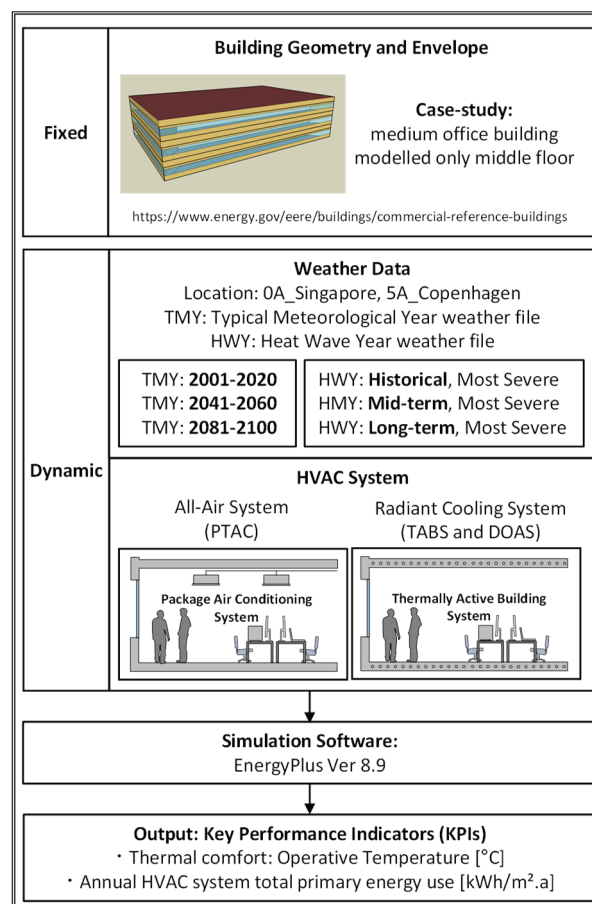
**Abstract.** Radiant systems have been proven to be an energy-efficient and resource-effective heating and cooling solution for buildings. A key feature of a thermally active building system (TABS), one type of a radiant cooling system, is its ability to activate and control the thermal mass of the building structure. The advantage of this feature is the peak load shifting effect by the thermal mass, which leads to energy saving compared to a conventional system, e.g., an all-air system. This feature of the radiant cooling system could be particularly beneficial under a heat wave and power outage event. Dynamic building simulations were carried out to quantify the resilience of TABS to heat waves and power outages. An all-air system (i.e., air-conditioning) was used as the reference cooling system. The simulations were carried out using EnergyPlus. Future weather files (typical meteorological years and years with heat waves) developed in IEA EBC Annex 80 were used for the simulations. In both HVAC systems. Simulation results for future weather data resulted in a decrease in heating demand and an increase in cooling demand.

## 1 Introduction

Climate change has become a severe problem globally, with natural disasters causing extensive damages [1]. In response to climate change, resilience of the built environment has been increasingly significant. There are a variety of shocks to buildings, such as floods, heat and cold waves, associated power outages, and earthquakes. This study focuses on heat waves and power outages. Previous studies have shown that frequent heat waves and power outages caused by climate change are significant disruptors that make it challenging to maintain Heating, ventilation, and air-conditioning (HVAC) systems [2-3]. If HVAC systems cannot maintain comfort conditions during events such as power outages, it could result in declining occupant productivity and health and having serious and long-term adverse economic consequences. Therefore, there is a need to identify effective resilient cooling solutions to deal with climate change.

International Energy Agency (IEA), Energy in Buildings and Communities Programme (EBC) Annex 80 – Resilient Cooling of Buildings [4] is working on defining resiliency and its key concepts in terms of building cooling [5-7], developing qualitative and quantitative key performance indicators [8] and evaluating different cooling systems based on these indicators.

Radiant cooling systems have been proven to be an energy-efficient and resource-effective heating and cooling solution for buildings [9]. A key feature of a Thermally Active Building System (TABS), one type of

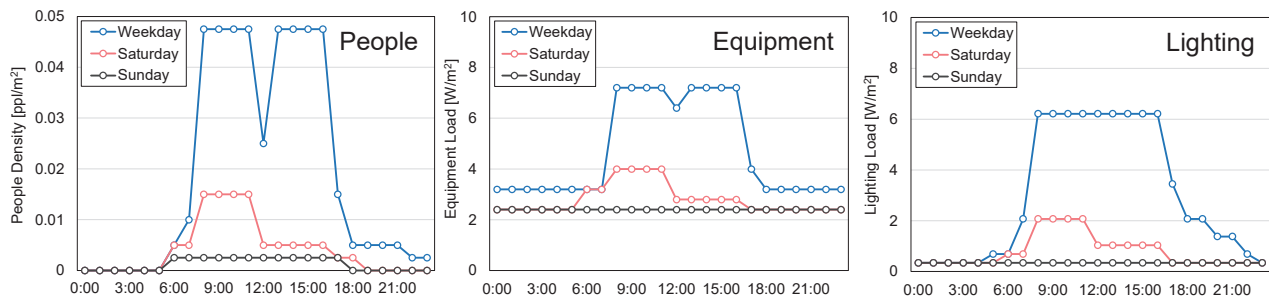


**Fig. 1.** Framework for evaluating the building resilience of different weather locations and cooling technologies

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**Table 1.** Construction and material of the building envelope

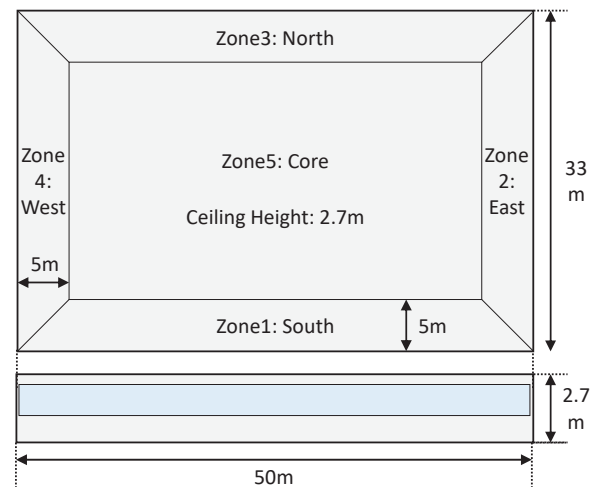
Construction	Material	R value [(m <sup>2</sup> ·K)/W]	Thickness [mm]	Conductivity [W/(m·K)]	Density [kg/m <sup>3</sup> ]	Thermal capacity [J/(kg·K)]
Floor/ceiling	Carpet pad	0.22	—	—	—	—
	Concrete	—	101.6	2.31	2,322	832
Outside wall	Stucco	—	25.4	0.72	1,856	840
	Gypsum board	—	15.9	0.16	800	1,090
	Insulation	2.37	—	—	—	—
	Gypsum board	—	15.9	0.16	800	1090
Interior wall	Gypsum board	—	25.4	0.16	800	1090



**Fig. 2.** Schedule of internal heat gain

a radiant cooling system, is its ability to activate and control the thermal mass of the building structure [10]. The advantage of this feature is the peak load shifting effect by the thermal mass, which leads to energy saving compared to a conventional system, e.g., an all-air system. This feature of TABS could be particularly beneficial under a heat wave and power outage event by natural disasters [11-12].

Fig. 1 shows the framework for evaluating the building resilience of different weather locations and cooling technologies. The present study compared the resiliency performance of TABS with that of a Packaged Terminal Air Conditioner (PTAC). Indoor temperature and primary energy consumption of the HVAC systems under typical weather conditions and future heat waves and power outages were compared.



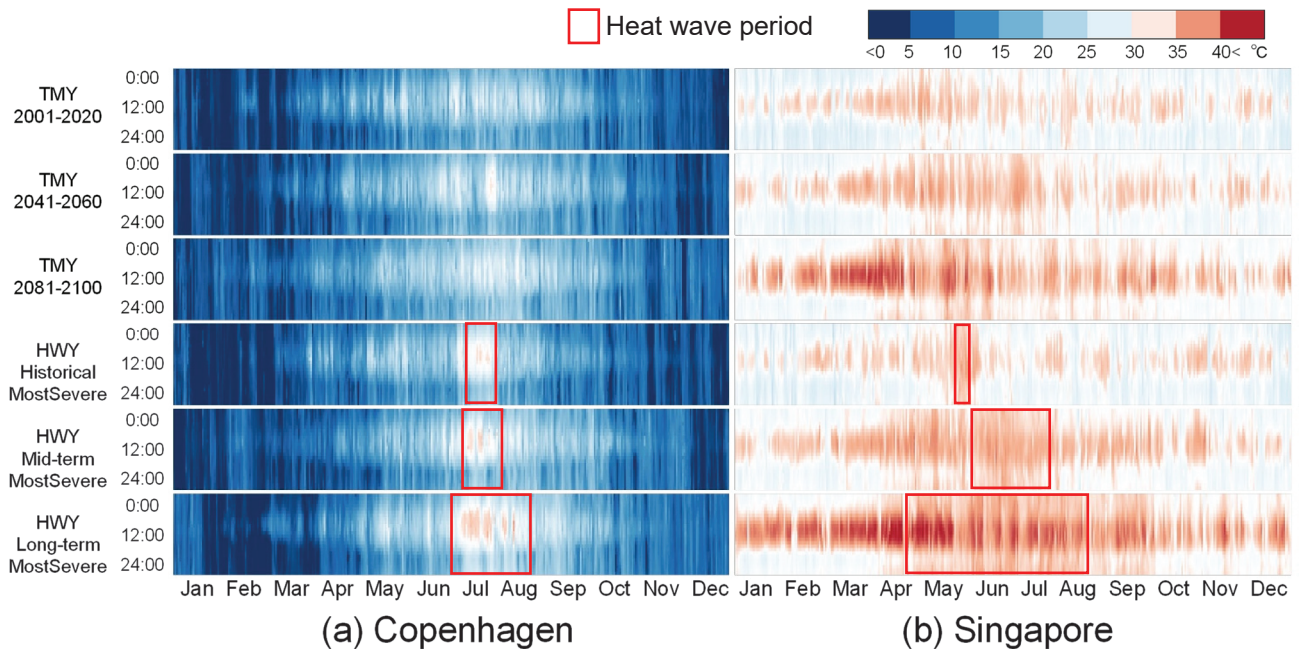
**Fig. 3.** Zone layout for medium office building

## 2 Methodology

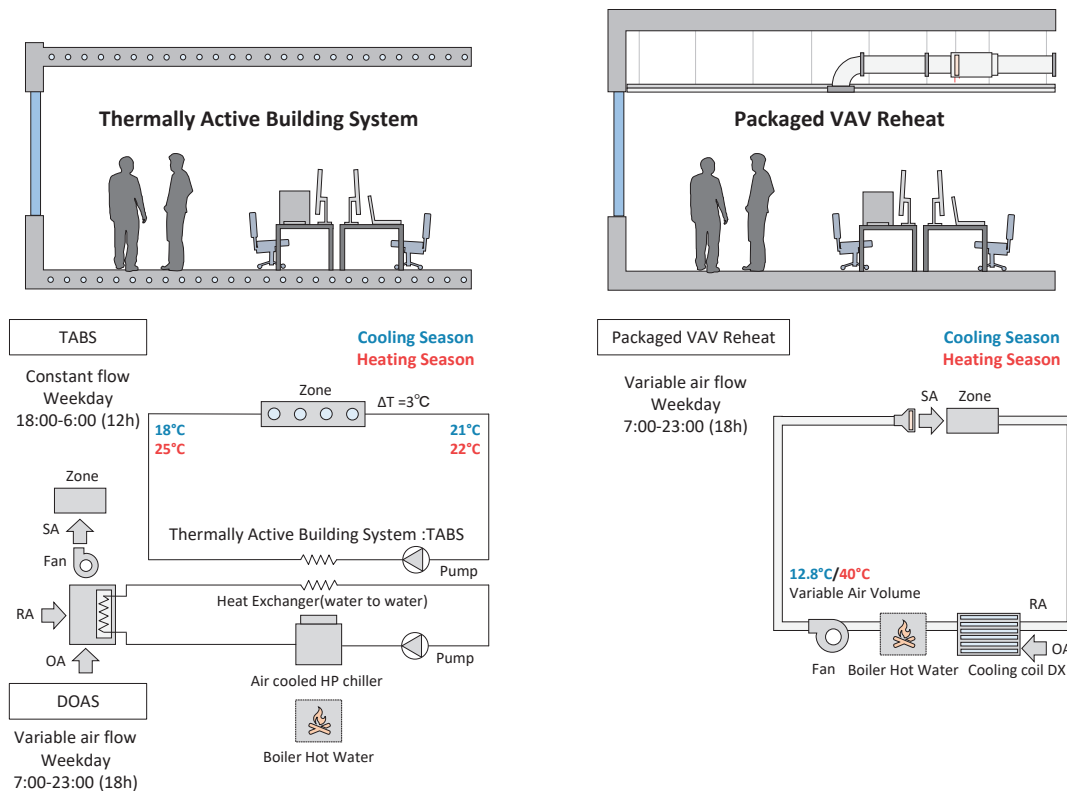
### 2.1 Building model

Fig. 2 shows the schedule of internal heat gain and Fig. 3 shows the zone layout of for the building model. A medium office building to represent commercial buildings, one of the prototypes building models provided by the U.S. department of Energy, was used for the simulations. The prototype building models are based on ANSI/ASHRAE/IES Standard 90.1 [13]. In this study, only the middle floor was modelled with the simulation software EnergyPlus version 8.9 [14]. The middle floor was separated in 5 zones, comprising 4 perimeter zones and a core zone. The construction and material of the building is presented in Table. 1. [15]

For the boundary conditions of the building, only the exterior walls exchanged heat with the external environment. The interior walls were set to adjacent, and the floor and ceiling were set to adiabatic. Air change rate of infiltration was 0.6 h<sup>-1</sup>. 30 m<sup>3</sup>/h of outdoor air was supplied per person by the ventilation system. Outdoor supply air for each zone was calculated based on ASHRAE Standard 62.1-2019 [16]. The maximum values of density of occupants, lighting gain, and equipment gain were 0.05 person/m<sup>2</sup>, 6.9 W/m<sup>2</sup>, and 8.0 W/m<sup>2</sup>, respectively. As shown in Fig. 2, the internal heat gain was varied according to the schedule. During power outage periods, all internal heat gain were set to zero.



**Fig. 4.** Outdoor dry bulb temperature



**Fig. 5.** Heat source system diagram

## 2.2 Weather data

The future typical meteorological year (TMY) weather files and future heat wave (HWY) weather files developed in Annex 80 [4] were used for the simulations. Singapore and Copenhagen were selected as representative very hot-humid and cold-humid weather locations. Heat balance simulations were run using three TMY files (2001-2020, 2041-2060, and 2081-2100) and three HWY files for most severe conditions (Historical, Mid-term, and Long-term), respectively. As shown in

Fig. 4, heat waves will be more frequent in both Copenhagen and Singapore in the future, and the duration of the heat wave period will be longer.

## 2.3 HVAC strategies

Fig. 5. Shows the heat source system diagram both PTAC and TABS. Two types of HVAC systems were modelled for comparison: TABS (coupled with a dedicated outside air system, DOAS) and PTAC. Input values and settings presented in this section were taken from [15-18]. Cooling setpoint was 24°C and heating

setpoint was 21°C. Setpoints were used air temperature. Annual simulations were conducted, i.e., the analysis period was from 1<sup>st</sup> January to 31<sup>st</sup> December. Simulation interval was 1 hour.

The PTAC operated from 7:00 to 23:00 on weekdays. The supply air temperature was maintained at 12.8°C and 35°C with a variable air volume fan during the cooling and heating season. The PTAC cools or heats the required outdoor air and return air. This supplies by coil cooling DX and reheat coil and supplies it to each 5 rooms.

The TABS was operated from 18:00 to 6:00 on weekdays. Cold or hot water was supplied to each room for a fixed period with variable water flow rates, depending on the heat load. The ceiling was set as the radiant surface, and the supply water temperature for the cooling and heating season was set to 18°C and 30°C. Pipe inner diameter was 0.020 m, and one circuit length of TABS is 106.7 m. Operative temperature was adopted for temperature control for TABS. DOAS was used to remove the latent heat load and the sensible heat load that could not be removed by TABS.

### 3 Results and Discussion

#### 3.1 Indoor thermal comfort

Table 3 shows the Percentage of time in comfort range (EN16978-2019) under future typical meteorological year weather conditions in Copenhagen. The period from May to September was set as the cooling season and the rest of the year as the heating season and operative temperature during occupied hours (8:00 to 17:00 on weekdays) were used. In office spaces, the default indoor operative temperature range corresponding to Category II of EN16978:2019 [19] is 20-24 °C for the heating season and 23-26 °C for the cooling season. Indoor operative temperature were kept within the comfort range for all cases for both TABS and all-air system. However, energy use related to the

**Table 2.** Boundary conditions of TABS [17-18]

Radiant surface	Ceiling
Supply water temperature	18°C (Cooling) 30°C (Heating)
Pipe inside diameter	0.020 m
Circuit length	106.7 m
Temperature control	Operative temperature

HVAC systems were greatly dependent on weather data and the selected system.

#### 3.2 Energy use and operational carbon

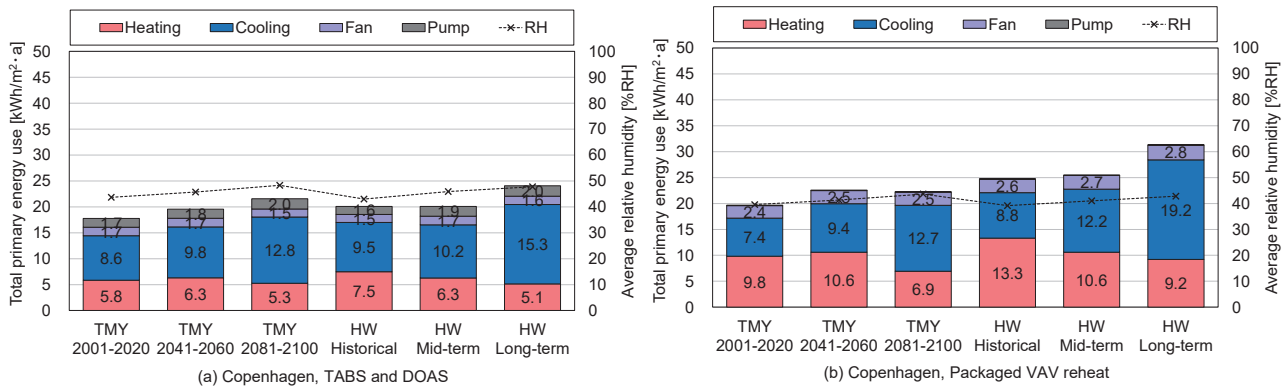
Fig. 6 shows annual HVAC system total primary energy uses per conditioned floor area. Annual cooling and heating primary energy uses per conditioned floor area are one of the Key Performance Indicators (KPI) for the IEA EBC Annex 80 – Dynamic simulation guideline for the performance testing or resilient cooling strategies [4]. The primary energy conversion factor are used to 2.5 for electricity and 1.1 for gaseous fossil fuel. [20] In Copenhagen, the primary energy use for cooling and heating of TABS was lower than that of PTAC. In both HVAC systems. Simulation results for future weather data resulted in a decrease in heating demand and an increase in cooling demand. Total primary energy use was expected to increase with future rising outdoor temperatures.

Fig. 7 shows annual HVAC system operational carbon per conditioned floor area. The carbon emission factor are used to 0.187 kgCO<sub>2</sub>-eq/kWh for electricity and 0.105 kgCO<sub>2</sub>-eq/kWh for gaseous fossil fuel [21]. Annual HVAC operational carbons for cooling and heating of TABS was also lower than that all-air system.

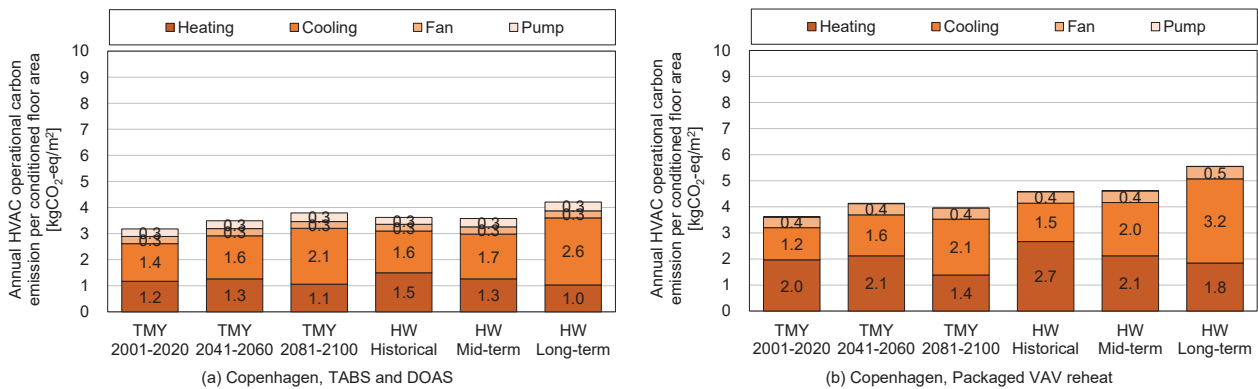
The primary energy use and operational carbon for cooling and heating in TABS were less than in the all-air system. Another advantage of installing TABS was

**Table 3.** Percentage of time in comfort range in Copenhagen (EN16978-2019)

HVAC System	Thermally Active Building System: TABS				Packaged VAV reheat			
	Average Operative Temp 5/1-9/30	EN16978 Category II 23-26°C 5/1-9/30	Average Operative Temp 1/1-4/30, 10/1-12/31	EN16978 Category II 20-24°C, 1/1-4/30, 10/1-12/31	Average Operative Temp 5/1-9/30	EN16978 Category II 23-26°C 5/1-9/30	Average Operative Temp 1/1-4/30, 10/1-12/31	EN16978 Category II 20-24°C, 1/1-4/30, 10/1-12/31
Unit	°C	%	°C	%	°C	%	°C	%
TMY 2001-2020	24.1	98	22.5	94	24.4	99	22.2	90
TMY 2041-2060	24.1	97	22.6	91	24.3	99	22.1	88
TMY 2081-2100	24.0	98	22.7	90	24.4	99	22.6	83
Heat Wave Historical	24.1	97	22.3	95	24.2	97	21.8	93
Heat Wave Mid-term	24.3	92	22.6	93	24.3	97	22.1	89
Heat Wave Long-term	24.2	98	22.7	95	24.5	98	22.2	92



**Fig. 6.** Annual HVAC system total primary energy uses per conditioned floor area in Copenhagen



**Fig. 7.** Annual HVAC system operational carbon per conditioned floor area in Copenhagen

that the energy/carbon increase in heat wave weather data from mid- to long- term was smaller for TABS than for the all-air system.

In this study, the comparison of PTAC and TABS should be done in terms of indoor thermal comfort, energy use, or maybe those simulations should consider the sizing of the systems as well. It should be noted that the typical operation of TABS is night operation only and the simulated buildings was low thermal mass.

It should be noted that under the boundary conditions of this study, the sizing of air conditioning equipment and heat sources were calculated automatically according to the heat load, resulting in a stable indoor environment and significant changes in energy consumption related to HVAC systems.

## 4 Conclusion

Dynamic building simulations were carried out to quantify the resilience of a thermally active building system and an all-air system (i.e., air-conditioning) to heat waves and power outages using EnergyPlus. Future weather files of typical meteorological years and heat wave years were used.

For any future typical meteorological years and future heat wave years, both TABS and PTAC were able to provide an indoor temperature within a comfortable range.

In Copenhagen, the primary energy use for cooling and heating of TABS was lower than that of PTAC. In both HVAC systems. Simulation results for future weather data resulted in a decrease in heating demand and an increase in cooling demand. Total primary

energy use was expected to increase with future rising outdoor temperatures.

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