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PHOTOVOLTAIC VAPOR COMPRESSION AIR CONDITIONING SYSTEM WITH PHASE CHANGE MATERIAL (PCM) STORAGE TANK

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ABSTRACT

This study will demonstrate the performance of a photovoltaic (PV) powered vapour compression cooling system connected to a Phase Change Material (PCM) storage tank. Three options were studied, namely (a) PV vapour compression with a PCM storage tank and an air-conditioned room with chilled water circulation with transparent membrane/desiccant; (b) PV vapour compression with a PCM storage tank and an air-conditioned room with chilled air dehumidification; and (c) PV vapour compression with a PCM storage tank and an air-conditioned room chilled by combined water circulation, a transparent membrane/desiccant, and air duct dehumidification. Simulation using TRNSYS, TRNBuild, and EES programmes has been conducted to determine the best indoor temperature and humidity options. The first simulation was for the room without cooling, where the room temperature reached 32.58°C at a time of 4146 hr. Then the rest of the simulation was carried out for options (a), (b), and (c) of the solar air conditioning PCM storage vapour compression system, The coefficient of performance (COP) for the system has been evaluated. It is important to note that the heat pump operates for 9 hours and the system operates for 24 hours, depending on the use of the system for cooling, reaching room temperatures at a rate of 4144.50 hours, which is 22.36 °C, 24.52 °C, and 23.56 °C, respectively. Both options (b) and (c) had about the same relative humidity inside the building with cooling, 56.66% and 59.69%, respectively, but option (a) had 100%. After 4144.50 hours of operation, the systems with options (b) and (c) had the lowest room dew point temperatures of 15.38 °C and 15.38 °C, respectively, followed by option (a) with a dew point temperature of 22.36 °C. Also, at the same time of operation (4144.50 hours), systems with options (b) and (c) had COP systems of 7.25 and 7.86, respectively, which were higher than option (a), which had a COP system of 6.9. A vapour-compression air conditioning system with PCM storage will make the system perform better.

Keywords: *PCM, storage tank, vapor- compression system, cooling, dehumidification, COP*

1. INTRODUCTION

The rapid growth of the global population and economy has resulted in a substantial rise in the demand and consumption of energy, leading to significant environmental consequences (Du *et al.*, 2018, Bloess *et al.*, 2018, Liu *et al.*, 2018, Peker *et al.*, 2018, Zia *et al.*, 2018, Husein and Chung, 2018, Kasaeian *et al.*, 2017, Zhou *et al.*, 2012). According to Eurostat data, European Union member countries' energy consumption increased significantly in 2015, reaching around 1084 million metric tons, with building-related sectors accounting for 39% of the total demand, or 422 Mtoe (Olivieri *et al.*, 2018). The construction sector is the predominant energy consumer contributing over one-third of the total energy utilization across the globe and is a significant contributor to CO2 emissions (Devaux and Farid, 2017). Studies suggest that HVAC equipment uses around half of a building's energy, although some research suggests this value could be as high as 60%(Young *et al.*, 2018, Akeiber *et al.*, 2016). The demand for cooling is projected to increase dramatically, from 0.8 EJ in 2010 to 5.8 exajoules in 2050. China, in particular, is predictable to surpass the cooling loads level of Latin America and Asia by 2040 (Saffari *et al.*, 2017b). In response to this situation, researchers and policymakers are advocating for more sustainable and energy-efficient buildings, exploring solutions for energy conservation and storage to mitigate the effects of global warming.

The creation of a cutting-edge technology aimed at improving energy conservation and efficiency within buildings is a crucial problem for governments and communities whose objective is to decrease energy usage while ensuring thermal comfort in varying weather conditions (Liu et al., 2016, Hasson *et al.*, 2022). Incorporating storage of thermal energy technologies within buildings leads to a decrease in the maximum load, separating energy requirements from the supply, facilitating the integration of Utilizing renewable sources of energy and ensuring effective thermic energy management, ultimately improving energy efficiency in buildings (Olivieri *et al.*, 2018). Due to their high storage of energy intensity, phase change materials have seen an upsurge in utilization in construction applications (Maccarini *et al.*, 2018).

The selection of PCMs for various applications should be done in accordance with the application environment. To enhance energy performance through simulation, (Saffari *et al.*, 2017a) conducted a study on the optimal melting temperature of PCMs in buildings. The findings of the study recommend that the melting temperature of PCMs be about 20 degrees Celsius in hotter areas and 26 degrees Celsius in cooler ones. (Mosaffa *et al.*, 2012) HVAC equipment with PCM thermal storage solidification was studied. A 29.7°C PCM provided thermal comfort. Despite having the same size and heating rate transmission surface area as the rectangular storage, the tubes and shell-finned thermal storage solidified PCM more quickly.

The study conducted by (Prabhakar *et al.*, 2020) aimed to integrate PCM storage of thermal energy in conjunction with ventilation of natural. The researchers optimized the melting temperature of the PCM based on the specific city. The findings showed that the optimal melting temperature of the PCM was between 22-26°C. Additionally, the study revealed that natural ventilation during nighttime hours in office buildings had a substantial energy-saving potential.

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(Li *et al.*, 2021) examined the compatibility of PV disruption with a directly powered compressor. The components evaluated were solar radiation, an appropriate compressor, the control by MPPT, and the PV panel's power output. In addition, the system used ice storage, which eliminated the need for a battery bank, decreasing both initial and ongoing costs. The findings revealed that the average efficiency of the system using the control by MPPT was 0.124, an improvement of 81.7% compared to the system without the controller, with the highest system COP reaching 0.289.

(Rahdar *et al.*, 2016) simulated the performance of an ice thermal storage system and a PCM tank using conventional cooling via vapour compression. Storage of thermal energy systems based on ice demonstrated lower power consumption and CO2 emissions by 4.59 percent and 17.8 percent, respectively, and it had lower power consumption and CO2 emissions by 7.58 percent and 27.2% than the PCM system, according to the comparison.

(Beck *et al.*, 2016) found that when surplus solar electricity from a PV system is stored in refrigerators and freezers, it may save up to 85% of the energy used in the reference system. If the batteries could be replaced with functional ice thermal energy storage, it may be determined that promoting the PV-powered air conditioner is a good concept.

There are currently reports of an air conditioning system without a battery bank using a PV-driven compressor. The Danish Technological Institute conducted a research project that was supported by the Danish Energy Agency beginning in 1999. (Pedersen *et al*., 2004). The ultimate objective is to create a vaccine cooler powered by solar energy that can operate without the use of batteries and makes use of a controller to enhance the compressor's performance in the course of the initial phase and consistent functioning at diverse levels of irradiance, it was observed that roughly 17 kg of ice could be generated. The importance of this study lies in its provision of attractive and eco-friendly alternatives for utilizing solar energy to cool buildings, in response to the issues of elevated pollution levels and limited access to clean electrical power.

2. THE COMPONENTS OF THE SYSTEM

In the first stage, the room was designed and built using the TRNBuild program, which is an assistant program that works with the TRNSYS simulation. The simulation procedure is divided into three major steps: The first step is to enter data from the active system and the building simulation into TRNSYS Simulation Studio. Both the building simulation and the TRNSYS Simulation Studio send data to the TRNBuild. To extract the final results, the second step is to process the data for each time step in a loop of exporting and importing data between two programs, TRNSYS Simulation Studio and TRNBuild. The third step is to display the results on a plotter or in tables. Fig. 1 depicts the flow chart steps for a dynamic building simulation using the TRNSYS and TRNBuild programs. The system's refrigerant cycle will then be developed by calculating fluid parameters (P, T, m, V, and so on) at all phases of the system using Newton's first and second thermodynamic principles. The TRNSYS and EES programs will then collaborate to create a solar hybrid cooling system known as the Photovoltaic Vapor Compression Air Conditioning System with PCM Storage Cooling System. The amount of thermal energy that must be removed from the system is then calculated, and the thermal balance is established.

Next, the amount of thermal energy to be removed from the system is calculated. A solar hybrid vapor compression with a PCM storage tank cooling system design was developed to make sure the system has enough cooling. After the room and solar heat pump system have been designed, the storage tank and ice gel are designed in TRNSYS and EES, respectively. A heat exchanger is then used to transfer heat between the ice gel cycle and a refrigerant fluid.

If the solar hybrid vapor compression with a PCM storage tank cooling system is suitable for the operating conditions, then the performance of the systems will be tested by numerical analysis using the TRNSYS program. Otherwise, the solar hybrid vapor compression with a PCM storage tank cooling system will be redesigned. The solar fraction, the economics, the cost recovery, and the greenhouse gases (GHG) were evaluated in the TRNSYS and ESS programs.

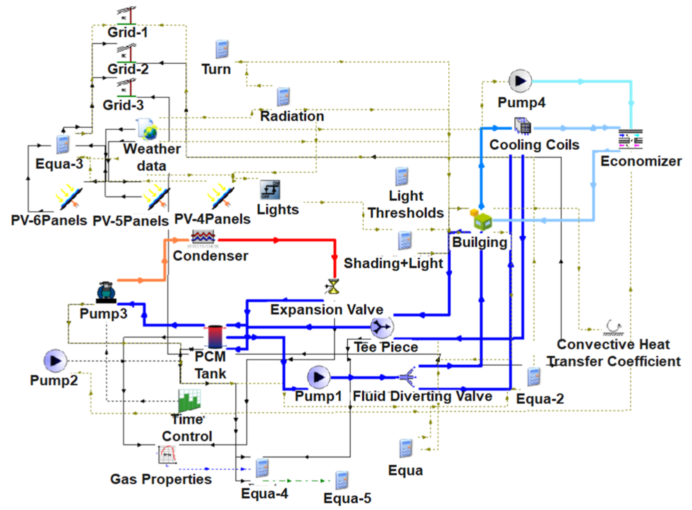

Fig. 1 TRNSYS model for PV vapor compression air conditioning system with PCM storage tank.

2.1 Dimensions of the System

The air conditioning systems have been designed based on the annual average load of a home in Malaysia. Components and cost optimization have been carried out. During the simulation, the following options are examined: Option (a) is a vapour compression with a PCM storage tank as shown in Fig. 2. Option (b) is an air-duct system as shown in Fig. 3, and Option (c) is a vapour compression with a PCM storage tank with an air-duct system as shown in Fig. 4.

Room: The typical room has an internal volume of (2.7 x 2.7 x 2.7) and an azimuth angle of 50 degrees south. The room has two sloping ceilings, each with a surface area of 8 m on each side at a 25-degree angle to the horizon, and two layers, Insul75 and Steelside, with thicknesses of 0.075 and 0.002 m, respectively. The direction of the first roof is E_270_25, while the direction of the second roof is W_90_25.

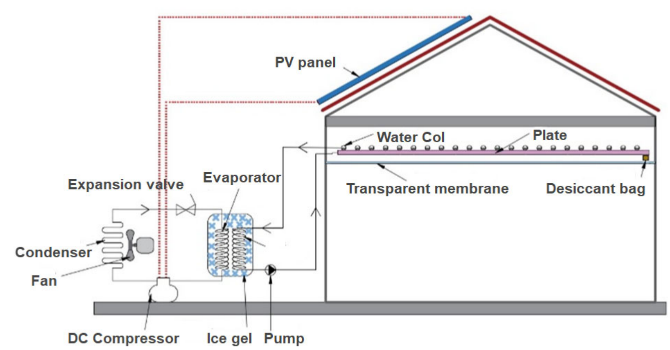

Fig. 2 Option (a) vapour compression with a PCM storage tank.

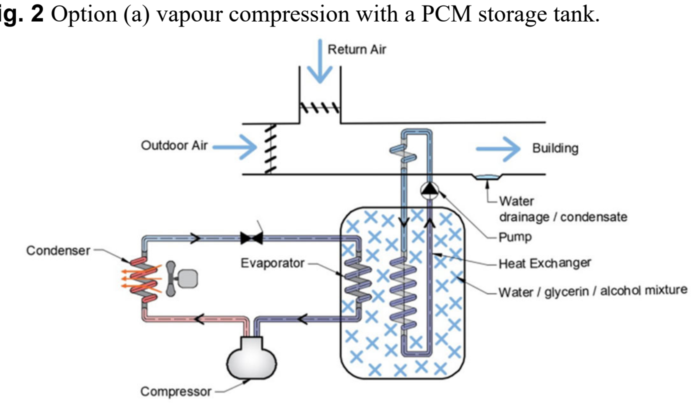

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Fig. 3 Option (b) air-duct system.

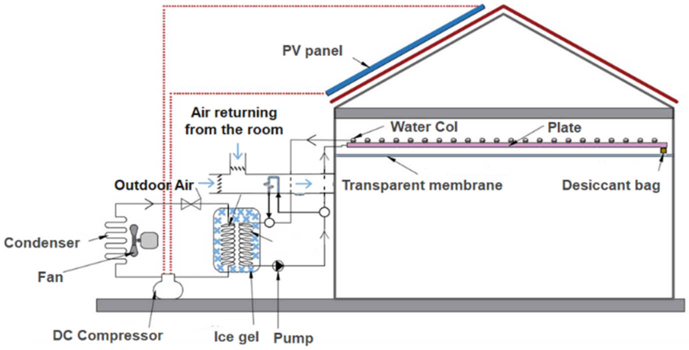

Fig. 4 Option (c) vapour compression with a PCM storage tank with an air duct system.

Chilled Ceiling: To model a radiant cooling system, an "active layer" is added to the ceiling. The layer is called "active" because it contains fluid-filled pipes that remove heat from the ceiling as shown in Fig. 5.

Active Layer Parameters:
specific heat coefficient of PCM Ice Gel = 3.287 kJ/kg K
pipe spacing (center to center) = 0.1 m
pipe outside diameter = 0.02 m
pipe wall thicknesses = 0.002 m
pipe wall conductivity = 1.26 kJ/h m K

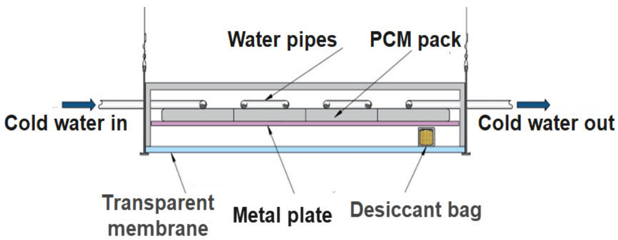

Fig. 5 The chilled ceiling.

Wall: The area of the four interior walls of the room is 2.7 m per wall. All walls are made up of four layers, the layers are plaster, brick, insulation, and plaster again with thicknesses 0.01, 0.1, 0.1, and 0.01 respectively. the directions of the wall are N_180_90, S_0_90, E_270_90, and W_90_90.

Floor: The inside floor area is 2.7m and its content four layers are floor, stone, silence, concrete, and insulation with thicknesses 0.005, 0.06, 0.04, 0.24, and 0.08 respectively.

Storage tank: The PCM tank used in this study is a storage tank that contains twin coils to increase the heat exchange efficiency between the PCM (ice gel) and a refrigerant fluid, The tank used is shown in Figure 6, Table 1 explains the specifications of the first and second coils in the storage tank on Fig. 6

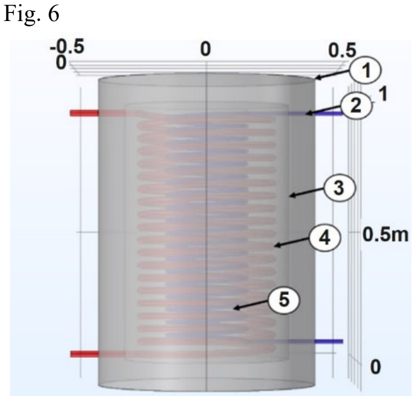

Fig. 6 Dimensions of both the storage tank's first and second heat exchangers.

Table 1. Specifications of both the first and second coils in the storage tank.

Number	*The part in the picture*	*Dimensions*
1	sheet	Thickness 1 mm
2	Insulation	Thickness 100 mm
3	Tank	Volume 0.3 m3
4	Second coil	length 31.5 m Number of turns 19
5	First coil	length 18.5 m and Number of turns 18

Cooling system: A 1 hp heat pump was used, operated by DC electricity power. The cooling system contents include a DC compressor, a condenser, evaporator, throttling valves as shown in Fig. 7.

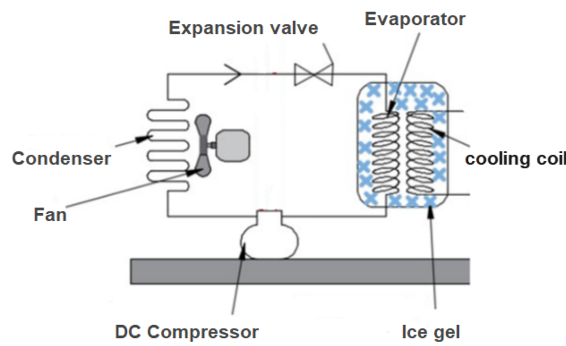

Fig. 7 Cooling system.

PV panel: The cooling system was used with a solar cell that embraces both inverter technology (VRF) and Full DC technology in the products, realizing that the domestic solar air conditioning can be directly operated by DC power from solar panels, without needing an inverter, controller or batteries. In this study, three PV systems containing 4, 5, and 6 solar panels were simulated, each solar PV cell producing an electrical power of 275 W.

Economizer: This component models an air-side economizer; a device which controls the amount of outside air brought into the building (when the building is in cooling mode) based on the ambient conditions, the zone conditions, and the cooling coil outlet conditions. The economizer is shown in Fig. 8

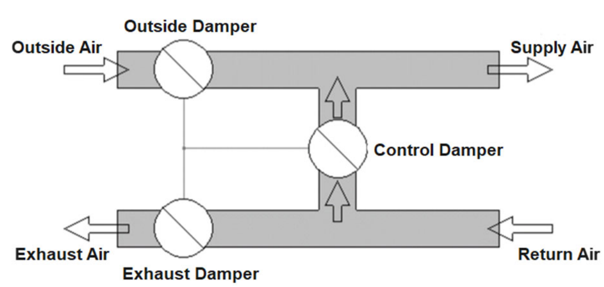

Fig. 8 Air Side Economizer Schematic.

PCM Ice Gel Materials: The PCM Ice Gel Materials material was designed in the EES program and according to the formula for mixing ingredients of water (92.5 %), Alcohol/ methanol (2.5 %), and Glycerin (5%). The thermal properties are shown in Table 2.

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Table 2. PCM Ice Gel Materials.

Materials	*Thermal conductivity* W/m.K	*Heat Capacity* kJ/kg.K	*Density* kg/m^3
Alcohol/ methanol	0.1983	2.535	786.3
Glycerin	0.2849	2.418	1259
Water	0.5948	4.183	997.1
Water (92.5%), Alcohol/ methanol (2.5%), Glycerin (5%), (PCM Ice Gel)	0.5694	4.054	1005

Cooling coil: The cooling coil is a coiled arrangement of pipes for the transfer of heat between the cooling fluid and air.

Fan coil: This device circulates and removes air from buildings. They are often linked to the ductwork that feeds and removes air from the interior and can offer ventilation, heating, cooling, humidity control, and filtration.

3. RESULTS AND OBSERVATIONS

For all the three options systems the main assumptions for this simulation namely (a) the simulation was conducted for the month of June (b) the time step of the simulation is every hour, (c) weather data used is for Kuala Lumpur, Malaysia and (d) the size of chiller is 1 ton. The work time for the compressor and chilled water system is 12 and 24 hours, respectively. The simulation was conducted for a whole month (June) where the room temperature inside the building for options (a), (b), and (c). It appears from the results that the lowest cooling temperature of the room was system (a) at the temperature of 22.36 C°, followed by system (b) at the temperature of 23.56 C°, and finally system (c) at the temperature of 24.52 C°. System (a) is considered the most efficient system for space cooling. Figure 9 shows a simulation time of 4144.50 [hr] for these results.

The relative humidity within the building with cooling was almost the same for alternatives (b) and (c), coming in at 56.66 % and 59.69 % respectively, but it was entirely unaffected for option (a). During the same period of operation at 4144.50 hours, as shown in Figure 10, It appears from the results that system (b) is considered the most efficient system to control relative humidity.

Figure 11 shows that options (b) and (c) had the lowest dew point temperatures in the room, at 15.38 Co and 15.38 Co, respectively, whereas option (a) had the highest dew point temperature of 22.36 Co for the same operating period of 4144.50 [hr]. Thus, the (c) system is the system that gives the lowest dew point temperatures in the room.

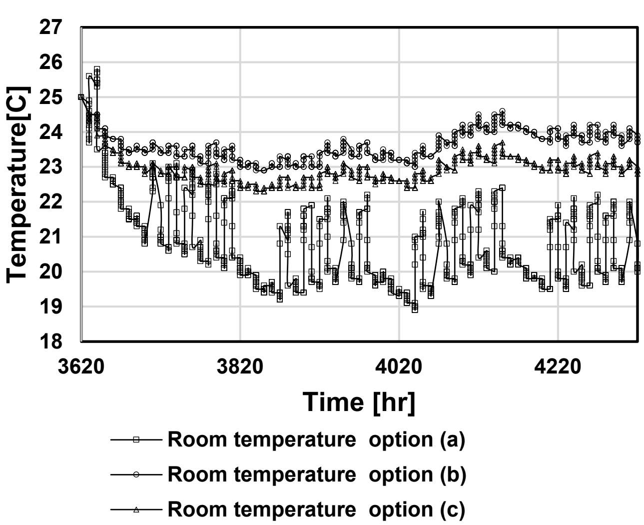

Fig. 9 Comparison of room temperature of the three options.

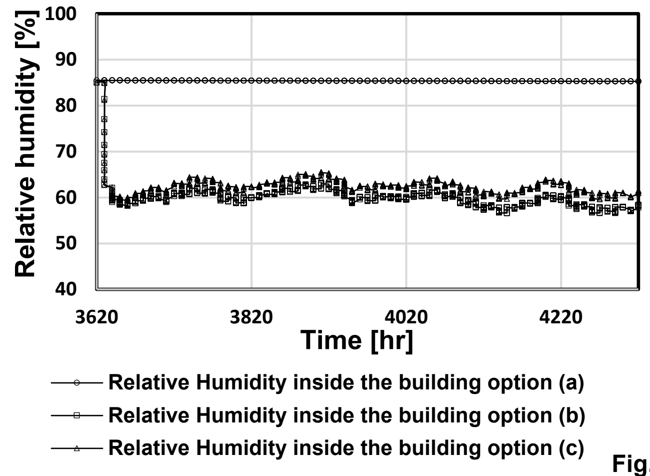

Fig. 10 Comparison of indoor relative humidity of the three options.

Furthermore, at the same time of operation at 4144.50 hours, the systems with options (b) and (c) demonstrated the higher COP systems of 7.25 and 7.86, respectively, followed by option (a) with a COP system of 6.9, Thus, the (c) system is the system that gives the highest COP. From all of this, we can say that (c) is the most reliable system to meet the needs of how the system works in Malaysia.

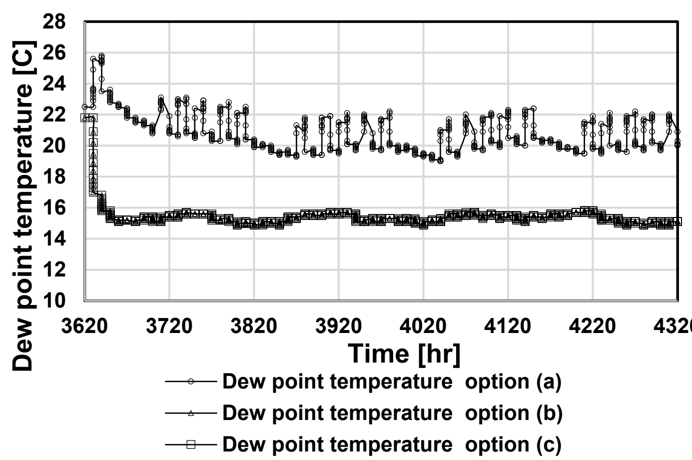

Fig. 11 Comparison of dew point temperature of the three options.

Figure 12 depicts the comparison between the power systems, Power PV and Power Grid, for the four, five, and six pieces of photovoltaic panels, as well as the solar radiation for these four days, for the system.

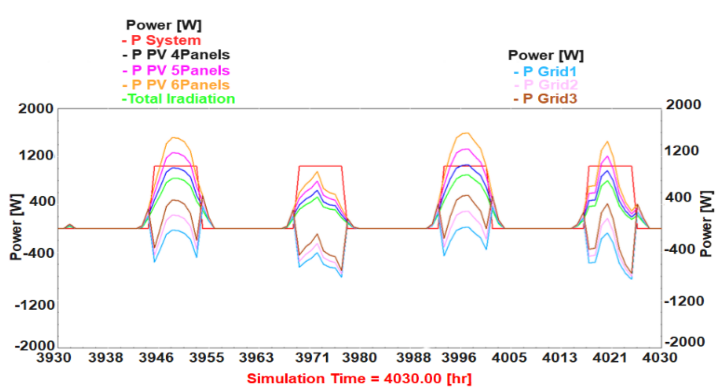

Fig. 12 Comparison between the power systems, Power PV, and Power Grid and solar radiation.

The annual electricity consumption and grid utilisation of various photovoltaic (PV) systems are depicted in Figures 13–15. Figure 13 presents the results for a four-panel PV system, which generates approximately 1.8 MW of electricity each year and consumes about 1.13 MW of electricity from the grid.

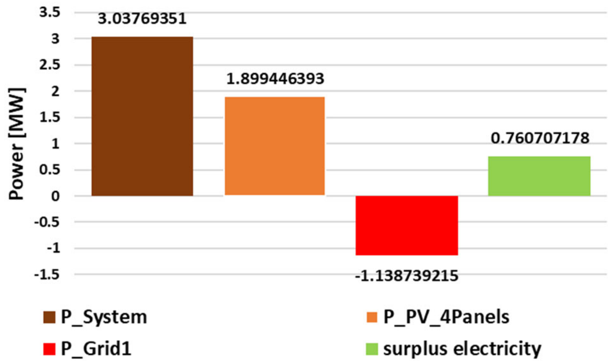

Fig. 13 The annual power of the system for four pieces of photovoltaic panels.

In contrast, Figure 14 displays the annual consumption results for a five-panel PV system, which generates approximately 2.3 MW of electricity each year and uses the least amount of electricity from the grid, about 660 kW.

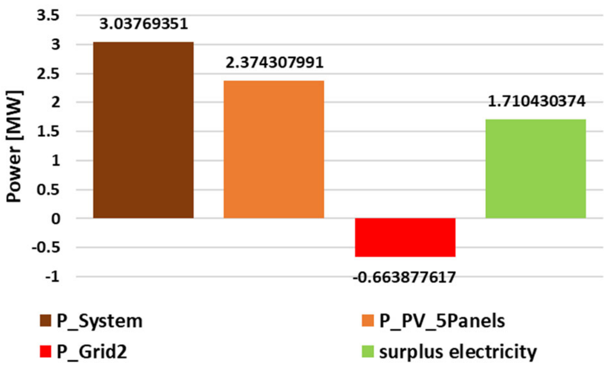

Fig. 14 The annual power of the system for five pieces of photovoltaic panels.

Finally, Figure 15 illustrates the annual consumption of a six-panel PV system, which generates the most electricity annually, approximately 2.8 MW, and uses the least amount of electricity from the grid, about 180 kW. Based on all of this, we can say that a six-panel PV system is the one that produces the most electricity under the operating conditions of the system in Malaysia.

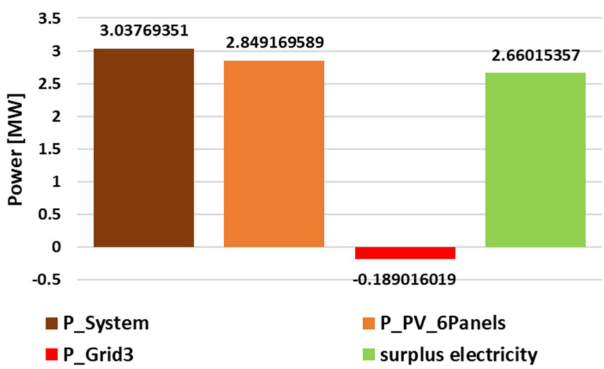

Fig. 15 The annual power of the system for six pieces of photovoltaic panels.

4. CONCLUSIONS

This study investigated a photovoltaic vapor-compression air conditioning system with PCM storage under different operating conditions using the TRNSYS program. The developed model showed that this system has several advantages, including low manufacturing cost, minimal maintenance, high efficiency, and low power consumption, all of which are beneficial to the environment by reducing pollution. The performance of three options for a photovoltaic (PV) powered vapour compression cooling system with a phase change material (PCM) storage tank was evaluated, which included options (a), (b), and (c). The simulation results showed that both options (b) and (c) had similar relative humidities inside the cooled building, at 56.66% and 59.69%, respectively, while option (a) had a relative humidity of 100%. Furthermore, at the time 4144.50 hr. of operation, systems with options (b) and (c) had higher COP systems of 7.25 and 7.86, respectively, compared to option (a), which had a COP system of 6.9. Additionally, systems with options (b) and (c) had lower room dew point temperatures of 15.38 °C and 15.38 °C, respectively, after the same duration of operation, while option (a) had a dew point temperature of 22.36 °C. These findings indicate the superior performance of a vapour-compression air conditioning system with PCM storage, which can achieve a higher COP and lower dew point temperatures. Overall, the findings suggest that this system is a viable alternative to traditional air conditioning systems and can provide improved performance in terms of energy efficiency and environmental impact.

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