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Article

Energy and Greenhouse Gas Emission Assessment of Conventional and Solar Assisted Air Conditioning Systems

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Abstract: Energy consumption in the buildings is responsible for 26% of Australia's greenhouse gas emissions where cooling typically accounts for over 50% of the total building energy use. The aim of this study was to investigate the potential for reducing the cooling systems' environmental footprint with applications of alternative renewable energy source. Three types of cooling systems, water cooled, air cooled and a hybrid solar-based air-conditioning system, with a total of six scenarios were designed in this work. The scenarios accounted for the types of power supply to the air-conditioning systems with electricity from the grid and with a solar power from highly integrated building photovoltaics (BIPV). Within and between these scenarios, systems' energy performances were compared based on energy modelling while the harvesting potential of the renewable energy source was further predicted based on building's detailed geometrical model. The results showed that renewable energy obtained via BIPV scenario could cover building's annual electricity consumption for cooling and reduce 140 tonnes of greenhouse gas emissions each year. The hybrid solar air-conditioning system has higher energy efficiency than the air cooled chiller system but lower than the water cooled system.

Keywords: sustainability; solar-assisted air-conditioner; building integrated photovoltaic; energy consumption; energyplus simulation; greenhouse gas emission; educational building

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1. Introduction

The increasing concern over rapid growth of energy consumption and the need for reduction of greenhouse gas emissions in building services has become one of the priority objectives when planning the design of new buildings [1,2]. However, the increased living standards, occupant comfort demands and building architectural characteristic trends, such as increasing application of transparent rather than opaque surfaces in the building envelope or even glass buildings, drive the growing energy demand for air-conditioning [3,4]. This occurs not only in residential and commercial buildings but also in the educational building sector. In the Australian higher education institutions majority of the universities are willing to invest in green technologies to improve environmental sustainability of their service [5].

The local availability of renewable energy sources should be considered a priority [6] for integration in sustainable green building designs. The effective use of natural energy sources contributes to significant energy demand reduction. Due to the unique geographical advantage of Australia, solar technologies seem to be promising sustainable technologies to power individual buildings. Australia has the highest average solar radiation per square metre of any continent in the world. The annual solar radiation falling on Australia is nearly 58 million petajoules (PJ), which is 10,000 times of Australia's annual energy consumption [7]. The Australian government has introduced a number of grants and passed incentive programs in favour of solar energy development [8]. Moreover, the intermittent character of the solar energy is in accordance with the human activity pattern in the commercial, governmental or educational buildings. The cooling demand occurs in the daytime when the activities are occurring in the building, and the demand reduces to the background level after the sunset.

There are two main types of solar energy technologies conceivable for the utility of solar radiation in cooling based on the electrical and thermal processes [3,7]. The electrical process is achieved by supplying the electricity converted by photovoltaic panels to a conventional motor driven vapour compression chiller. Because of the use of the traditional motor in this process, the main focus of research is based on renewable energy studies and development of integrated photovoltaic (BIPV) panels. The potential available areas in a building planned for the installation of PV panels typically include the horizontal building surface, which is the roof. However, the window area of buildings should also be carefully examined, as windows are important elements of building façades with full exposure to the outdoor environment, especially for the cases with large glazing areas. The building's glazing features are relevant for not only building's indoor environmental quality [4] but also building's energy efficiency [9]. Peng [10] compared the function, cost and aesthetics of the BIPV technology with traditional photovoltaic panels and proposed a novel structural design scheme to solve the maintenance and replacement difficulties for the PV panels. Miyazaki [11] and Wong [12] verified the application potential of semi-transparent PV panels as façades in office buildings, but they pointed out that the PV cell density could influence the efficiency of the power generation due to the increase of panel temperature. Yu and Halog [13] proposed a life cycle assessment (LCA) approach to evaluate cost-benefits of PV system components through a case study.

The thermal process used for cooling applies solar collectors to provide heat for the cooling process. The energy collected from solar radiation is used to satisfy the thermal energy requirement of a desiccant cooling system. Enteria [14] analysed a solar-desiccant air-conditioning system and found the solar collector was able to provide 82.8% energy and 80.6% exergy of the required system. Zhai [15] reviewed the traditional solar single-effect absorption cooling systems and introduced several new design options. The cooling efficiency of the solar cooling systems was assessed by Chemisana [16]. He claimed that a solar concentrating system would effectively increase the efficiency of the chiller.

In addition to the main solar cooling technologies listed above, a new approach based on both electrical and thermal processes, a hybrid solar air-conditioning (HSAC) system, was proposed by Ha and Vakiloroaya [17]. Inclusion of a solar thermal unit into the traditional cooling cycle utilises the solar thermal energy for refrigerant overheating after the compressor and increases its pressure. This is achieved by a vacuum solar collector positioned after the compressor, and the use of solar radiation as a heat source to heat water in an insulated water storage tank. The refrigerant from the compressor moves through a copper coil inside the tank and exchanges heat with the heated water. Therefore, the vacuum solar collector further heats the refrigerant to reach the required gas pressure at the condensed process in order to reduce the required electrical energy to run the compressor. Hence, the compressor of the system could be smaller sized, which ultimately results in a considerable amount of electrical energy saving when compared to the HSAC system. Figure 1 illustrates a schematic diagram of the system.

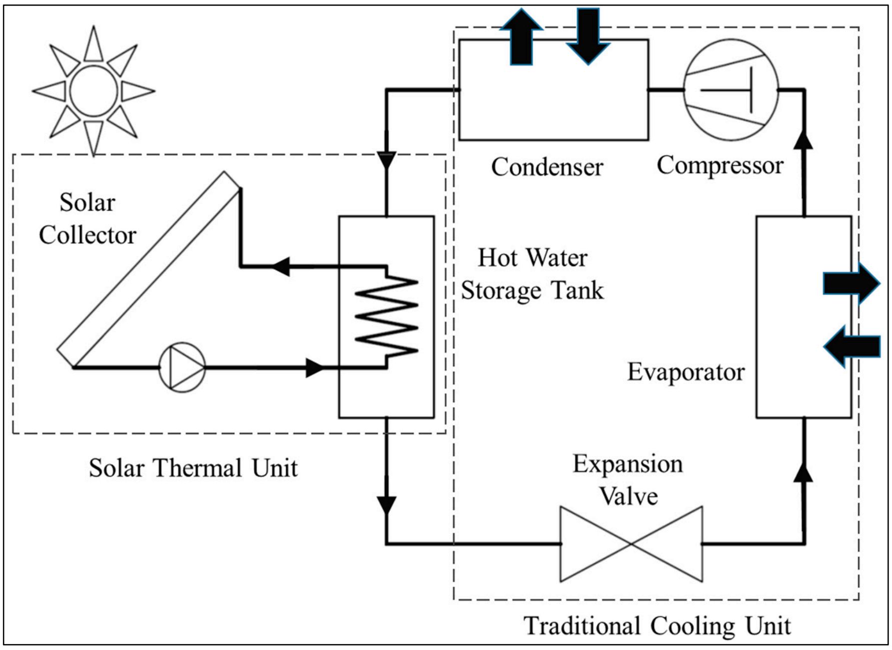

Figure 1. A schematic diagram of the Hybrid Solar Air Conditioning system (HSAC).

The aim of this study was to investigate the potential for reducing cooling systems' environmental footprint with approach of alternative renewable energy source. The work further to compares the cooling efficiency and the environmental burden of a solar powered conventional cooling system and a hybrid solar air-conditioning system in an existing educational building. Detailed numerical model of the case study building was developed to analyse the cooling energy consumption of the different cooling systems. A 3D geometrical model was further established to predict the renewable energy generation. The work in this paper aimed to obtain the energy supply strategy for a building's cooling systems with minimum environmental footprints, which, in turn, was expected to improve the building's energy consumption profile.

2. Methodology

2.1. Building Description

The newly built library at Macquarie University in Sydney, Australia was selected as a case study. The building is located at the centre of the campus and at the south side of seven existing multi-story buildings. The new library building, which is currently undergoing assessment for a Five-Star Green Building Rating [18], is comprised of five stories, equal to a total of 16,000 m^2 in the Gross Floor Area. The building has a capacity of 3000 seats able to accommodate nearly 3000 students and 150 library staff. The underground level and ground level of the library are the largest floors and provide access to the exhibition spaces, the main collection section with open shelves and some dedicated areas for presentation practise. The upper ground level, first, second, and third floors provide staff, students and postgraduate researchers adaptive personal and collaborative learning spaces. The design of the building was following the architectural trend with large glazing area and metal slabs for shading. Figure 2 presents a 3D view of the new library with its adjacent buildings. The 3D building model was firstly constructed in AutoCAD based on the architectural drawings and field measurements. The model was then exported to the simulation software for specified analysis. The envelope materials and thermal properties of the building are displayed in Table 1.

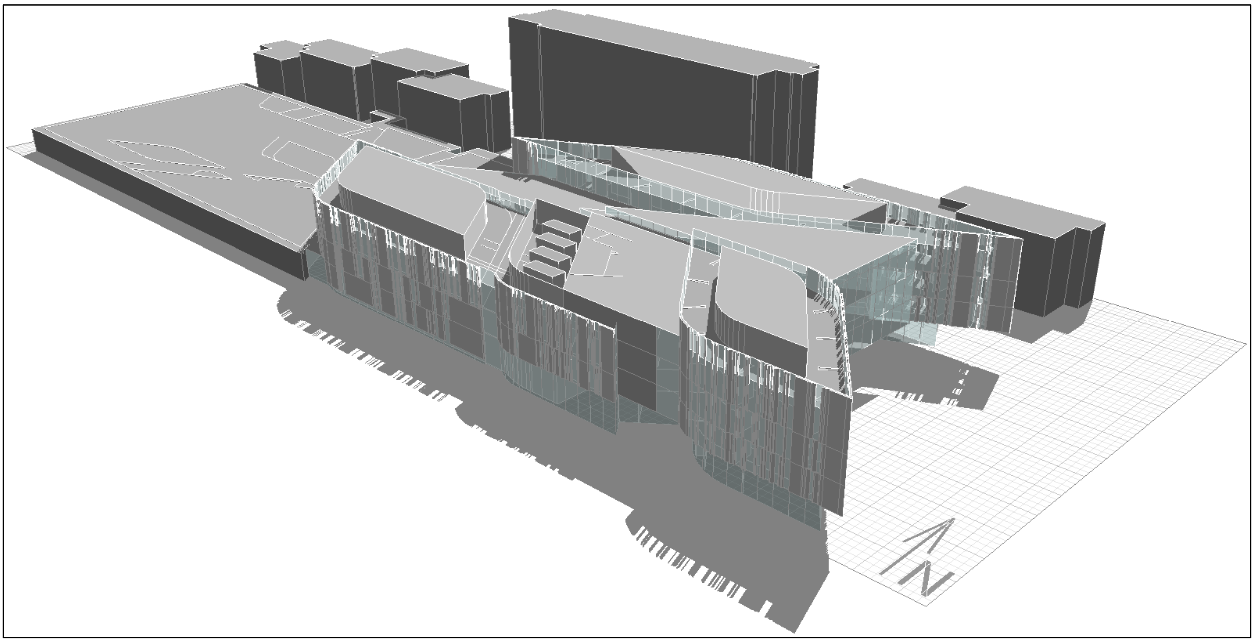

Figure 2. 3D view of the new library building.

Table 1. Envelope materials and thermal properties, including R-value, U-value, visible light transmittance (VLT) and solar heat gain coefficient (SHGC).

Constructions	R m^{2}K/W	U W/m^{2}K	VLT %	SHGC
External wall (lower ground and ground level)	1.78	0.56	-	-
Roof (flat roof and metal roof)	3.28	0.311	-	-
Glazing (windows and curtain walls)	-	1.69	62	0.29

2.2. System Description

A total of six different computer modelling scenarios of potential air conditioning systems were developed, as shown in Table 2. This study involved an assessment of conventional cooling methods based on water and air cooled chillers, and the emerging hybrid solar air-conditioning system. Each of these systems were assessed based on two different power supply scenarios, the first when the electricity was supplied from the grid and the second when the electricity was produced from photovoltaic PV cells installed to the maximum capacity on the same building. In this study, the HSAC case covered in Scenarios 5 and 6 were based on simulation using the data provided by the prototype testing results from Ha and Vakiloroaya [17]. The total amount of electricity generated by PV cells in Scenario 6 was expected to be less than the other scenarios, since part of the solar harvesting area on the building roof compromised of the solar thermal collector, which is essential for the HSAC system.

Table 2. Energy modelling scenarios and cooling system types.

Building	Cooling Method	Cooling Equipment	Energy Source	Scenario
Cooling Demand	Conventional System	Water Cooled Chiller (WCC)	Grid	1
			PV	2
		Air Cooled Chiller (ACC)	Grid	3
			PV	4
	Solar Assisted System	Hybrid Solar Air Conditioner (HSAC)	Grid + Solar Thermal	5
			PV + Solar Thermal	6

2.3. Solar Simulation Description

Advanced building performance simulating methods and developed software tools enable evaluation of building design and examination of energy source to approach reliable energy efficiency [6,19]. In this work, a model was developed using Autodesk Ecotect Analysis 2011 [20] to simulate the potential for generating solar power in this building. Ecotect is a visual building design and environmental analysis tool that links 3D modelling with a wide range of simulation and analysis functions [21].

The function of solar radiation calculations was applied to predict the annual accumulative solar radiation falling on the surface of the library building selected for this case study. The detailed geometrical model of the library as well as the building, which could potentially influence the library's solar exposure, was created in the software, as shown in Figure 2. The North, East and West sides of the library were set as the main analysis objects due to the direct sunlight (southern hemisphere). Refined mesh was then mapped over the building surfaces on these sides. When simulation begins, Ecotect uses hourly recorded direct and diffuse radiation data from the weather files obtained from the United States Department of Energy to calculate the amount of solar insolation. After the simulation, the analysis results can be overlaid on building surfaces in addition to the standard graph and table-based reports.

2.4. Energy Simulation Description

The energy simulation consisted of two stages, the simulation of building's cooling demand throughout the whole year and the evaluation of energy consumed by the building's cooling systems to satisfy the cooling demand, respectively. The first stage of energy simulation, the building's cooling demand, was carried out using EnergyPlus software [21], which is a building energy analysis and thermal load simulation program capable of running dynamic analysis based on the instantaneous measured weather data [22,23]. The second stage simulation was the cooling load profile calculated through the EnergyPlus and conducted on the basis of the outcomes of the first stage simulation.

2.4.1. Cooling Demand Simulation

With the input of the building's geometrical and thermodynamical properties associated with mechanical and other systems, the cooling loads necessary to maintain thermal control set points of the investigated building could be calculated. The predominant method used to simulate the dynamic cooling loads is the heat balance method. Along with Table 1, Table 3 lists simulation parameters adopted for the building's loads calculation. According to the table, the internal heat gains were mainly from three parts, occupancy, lighting and equipment, and infiltration.

Table 3. Simulation parameters of the building at different levels (lower ground level, ground level and the subsequent three floors).

Parameters	Units	Design value	
		LGL, GL	L1, L2, L3
People Density	people/m^2	0.2	0.1
Metabolic heat	W/person	135	123
Equipment heat	W/m^2	5	15
Lighting heat	W/m^2	12	10
Cooling set point	°C	25	25
Relative humidity	%	60	60
Ventilation/Infiltration	V/h	0.3	0.3

The metabolic heat generated from the occupancy at the building's peak occupancy level was estimated according to the Australia Standard 1668.2-2002. The standard states that each person should have space allocation of at least 5 m^2 in the general library area (Lower Ground Level and Ground Level) while in the study areas (Levels 1, 2 and 3), the space allocation should be a minimum of 10 m^2 per person. The number of occupants in the library varies in a typical academic year according to the learning sessions. Figure 3 represents the fraction of building occupancy throughout the year with three semesters, indicating clearly high usage exam weeks, mid-semester breaks and holidays.

The occupancy rates of a typical week, weekend and exam day were estimated based on the actual occupancy door counts measured at the entrance of the library. The hourly data of the number of occupants was collected during daytime from 8:00 to 18:00 and at night time from 19:00 to 22:00, over an investigation span period of 14 days, including nine weekdays, four weekend days and one session break day. The investigation results are shown in Figure 4.

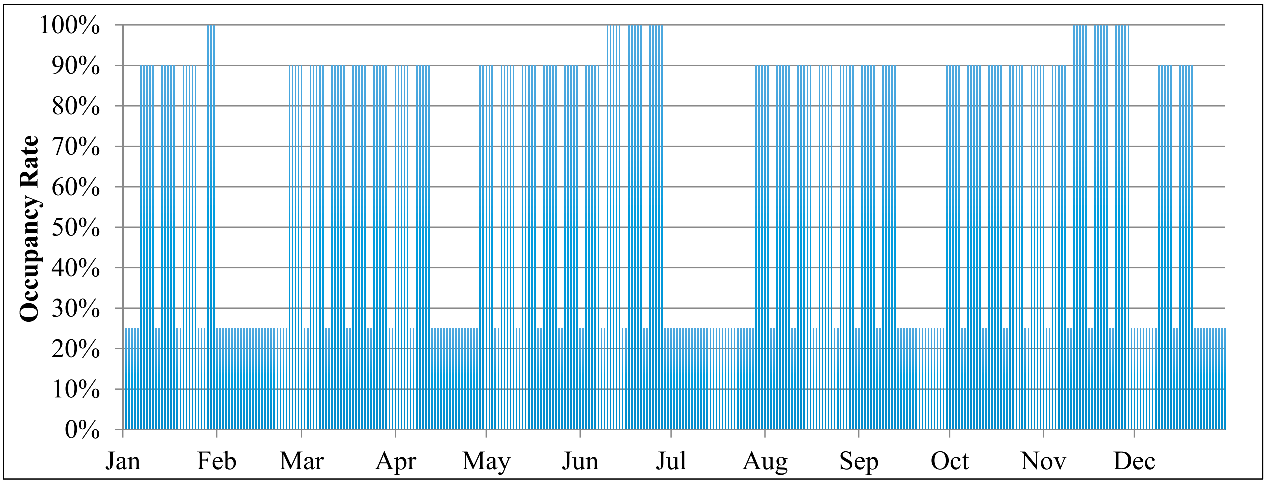

Figure 3. Annual occupancy schedule for the library building.

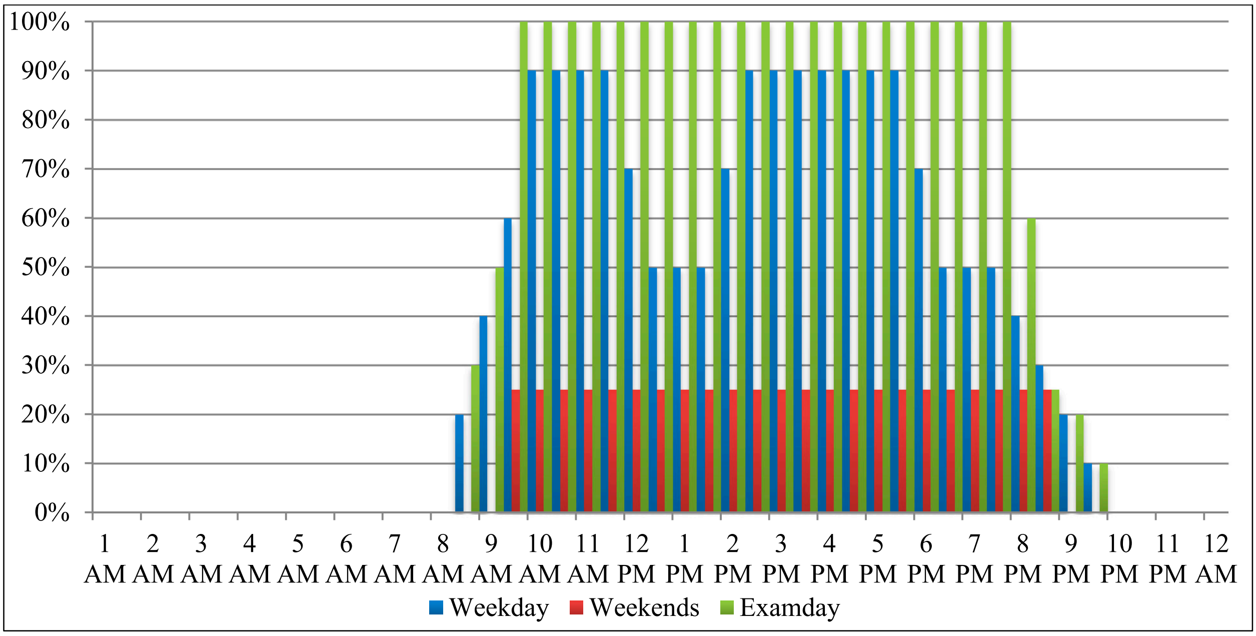

Figure 4. Occupancy profiles for weekdays, weekends and examination days.

The library opens at 8:00 and closes at 22:00 on weekdays, while it opens at 9:00 and closes at 21:00 on weekends and holidays. For a normal semester day (shown in blue in Figure 4), some students arrive early in the morning to occupy a study place for the remainder of the day. Other students and staff enter the building to borrow books and leave before the start of their course. At noon, the number of fixed students in the library drops as the students leave for lunch, but the number of borrowers entering the building is stable. After lunchtime, the students are back to study until the closing time of the building. The number of borrowers sharply decrease from 17:30 after the lectures finish. For an examination day, students arrive in the library earlier and leave the building later than the normal days. For the weekends and holidays, there is a smaller number of borrowers, but those who use the library for study remain in the building.

Artificial lighting and the usage of office equipment are the two additional sources of internal heat gains. The lighting and equipment running hours are assigned according to the occupancy schedule.

When the building is occupied, the lighting and equipment are on and stay at high levels to satisfy demands. The lights and equipment are back to standby mode after the building is empty. Figure 5 represents the detailed schedule and power density as determined according to field investigations. There is no difference between examination days and typical weekdays.

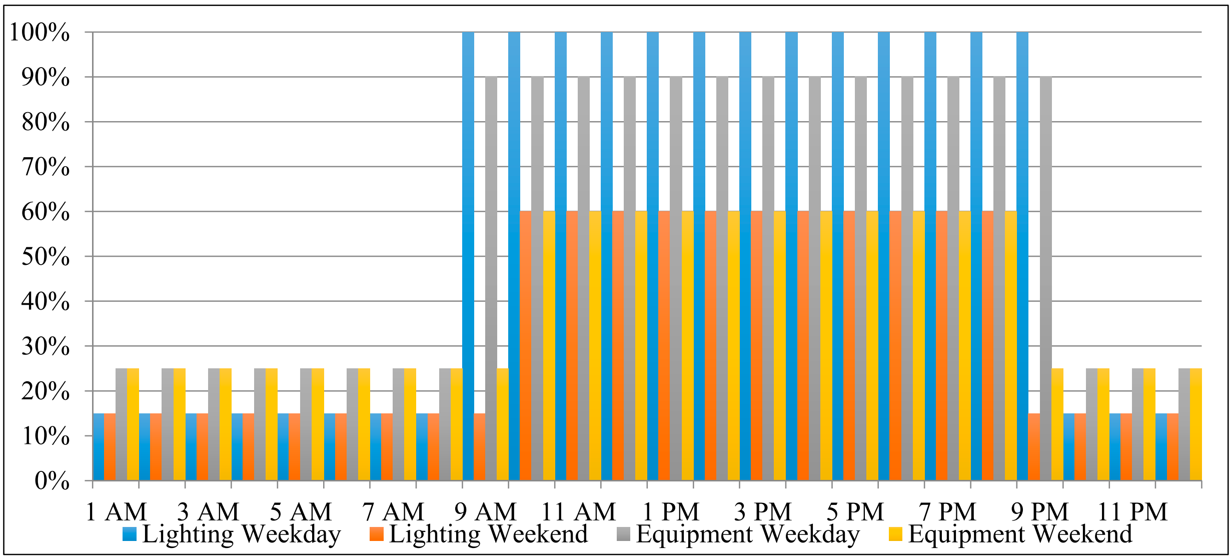

Figure 5. Lighting and equipment profiles for weekdays and weekends.

2.4.2. Energy Consumption Simulation

The energy consumption simulation of cooling systems could be conducted using the HVAC modules provided by the EnergyPlus, based on ASHRAE Standard 90.1-2013. By defining the simulation parameters of the building and the performance profile of the cooling systems, the dynamic energy consumption profile of the conventional cooling systems (water cooled chiller (WCC) and air cooled chiller (ACC)) could be calculated based on the local weather data, since the HVAC modules in the software have been fully established and verified to represent the working process of these systems due to their technical maturity and wide applications. However, when it comes to the HSAC, which is a relatively new system and is not included in the HVAC template, its parameter setup in EnergyPlus will not describe the system's working mechanism and will, in turn, affect the reliability of the simulation outcomes. Therefore, an alternative approach was applied where the energy consumptions of these three systems were evaluated offline on the basis of their coefficients of performance (COPs) and the cooling load profile obtained through the previous stage.

2.5. Greenhouse Gas Emission Prediction

The greenhouse gas emissions of cooling systems for the six scenarios are calculated using the following Equation (1):

$$GHG_{Total} = g_{Grid}E_{Grid} + g_{PV}E_{PV} - (g_{Grid} - g_{PV})E_B \quad (1)$$

where, g_{Grid} and g_{PV} are the specific CO_2 emission factors for electricity from the grid and PV panels, respectively; E_{Grid} stands for the cooling systems' electricity consumption supported by the grid while

E_{PV} represents the consumption share covered by PV generation; E_B represents the electricity balance left from the electricity generated by PV panels subtracting the electricity consumed by the cooling systems, $E_B = T_{PV} - E_{PV}$, in which T_{PV} is the total electricity generated by the PV panels. The emission factors in the equation are found in [24,25] and listed in Table 4.

Table 4. Average greenhouse gas emissions expressed as CO_2 equivalents for individual energy generation technologies.

	g $CO_{2\text{-}e}$/kWh
New South Wales electricity grid	900
Photovoltaic	90

3. Results

3.1. Solar Energy Potential

The solar energy potential of the library building selected for the case study in this work was further modelled with Ecotect 2011. The results, shown in Figure 6, reveal that solar radiation falls on the roof areas of the library building across the entire year. The majority of the exposed area received around 1687 kWh/m^2/year of radiation, while parts of the roof reached 1020 kWh/m^2/year due to the shading effect from the adjacent building components.

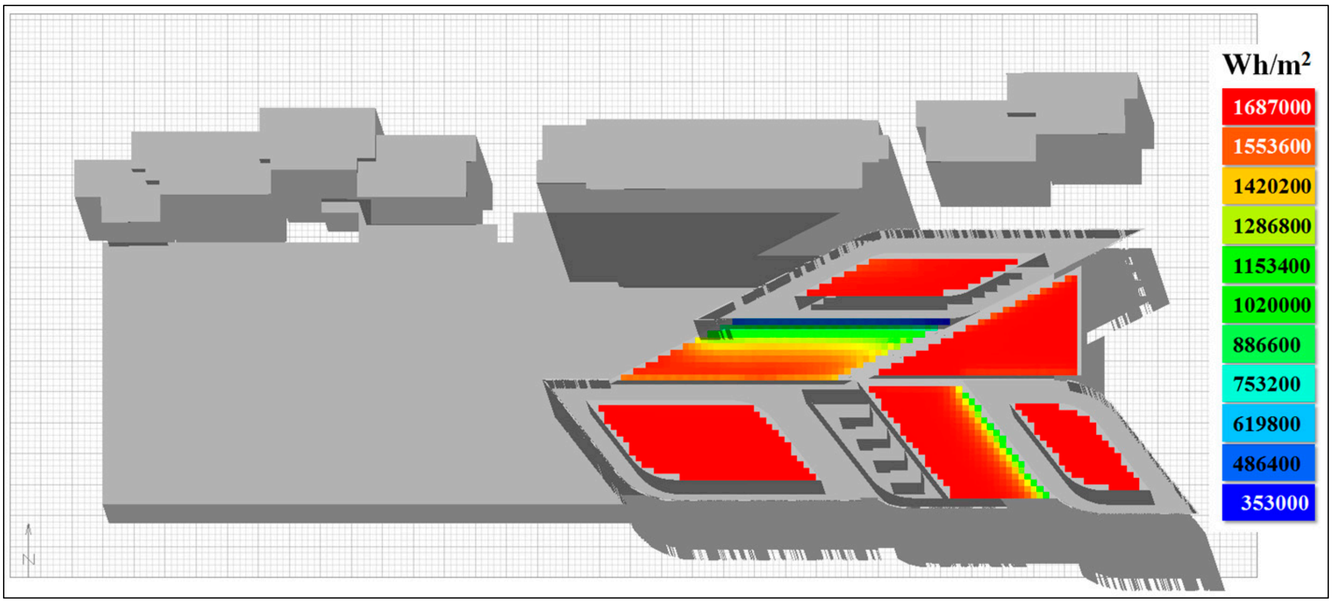

Figure 6. Annual cumulative solar radiation on the roof of the building.

With the advent of the third generation PV panels, the envelope of the building, including windows, can be used as solar electricity generators. Figure 7 illustrates the power generation potential using transparent PV panels on the East, North and West building surfaces. The colourful stripes on the building envelope represent the varied cumulative amount of the solar radiation, from the lowest at 49 kWh/m^2/year in the darkest area, to the highest 910 kWh/m^2/year on the Northwest glass curtain wall. The dark blue areas are the surface parts behind the vertical shading blades, which are rarely exposed to sunshine. Due to the different angles of the blades fixed on external walls or windows, the shading effects on the building envelope vary. Although the shading slabs nearly cover all the building surface area, the effective radiation area (over 80 kWh/m^2/year) still reaches a total of 1500 m^2. In this study, two types of PV panels were selected and calculated under an ideal condition without the efficiency decrement caused by the cell temperature increase and dust cover. The results were compiled in Table 5.

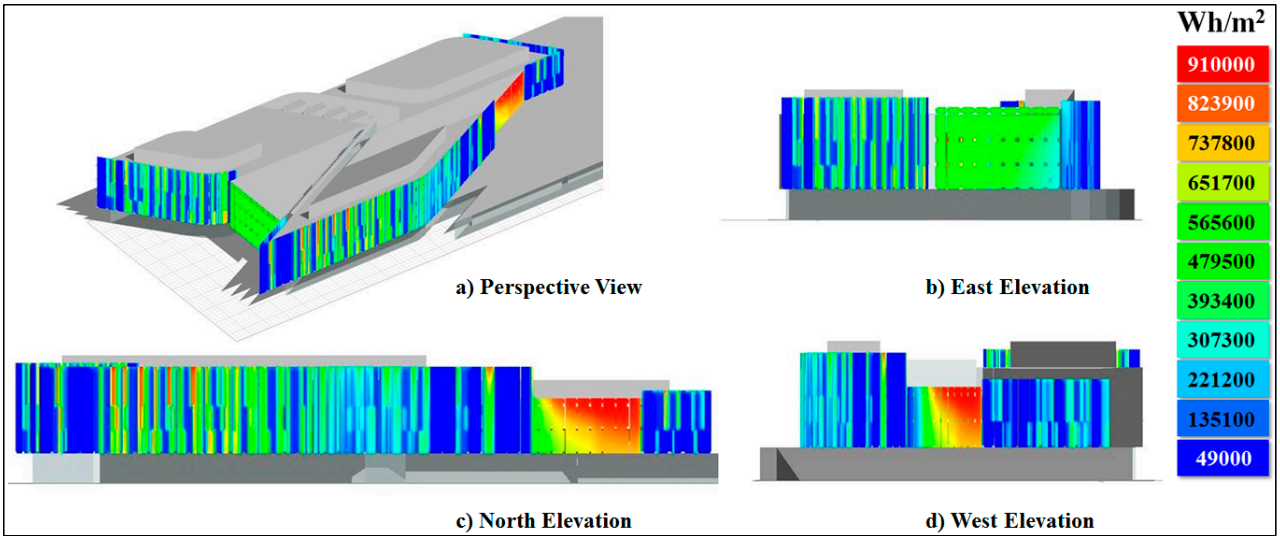

Figure 7. Annual cumulative solar radiation on the envelope of the building.

Table 5. Photovoltaics (PV) panel attachment and energy production analyse results.

Building Surfaces	PV Cell Types	Efficiency	Area of Panels [a] m^2	Available Solar Radiation MWh	Electric Power Generated [b] MWh
Roof	Multicrystalline	15%	1474 (1374)	2311.7	346.8 (323.3)
East side	Amorphous	8%	708	204.7	16.4
North side	Amorphous	8%	609	174.9	14.0
West side	Amorphous	8%	744	206.1	16.5
SUM			3535 (3435)	2897.4	393.7 (370.2)

Note: [a]: The area of PV panels in Scenario 6 was less than Scenario 2 and 4. This is because part of the photovoltaic cells on the building roof has to be replaced by the solar thermal collectors essential for the HSAC system; [b]: The electricity generated on the building roof for Scenario 6 therefore dropped from 346.8 MWh to 323.3 MWh per annum.

3.2. Cooling Demands of the Building

The first stage of simulation comprised of a pilot run on a summer day to determine the size of the cooling system. The cooling demand was calculated based on the design day information of the EnergyPlus IWEC weather file. According to the file, 21 February was selected as the summer design day and the dry bulb temperature of the day was 33.5 °C, while the wet bulb temperature was 23.3 °C. Figure 8 shows the outdoor temperature and its relevant cooling demand through the whole day. The outdoor temperature reaches peak of 33.5 °C at 15:00 when the cooling demand rises to the maximum value of 1138 kW in the following hour at 16:00. This lag is caused by the thermal storage property of the external walls. More specifically, the cooling demand between 12:00 and 13:00 experiences a temporary decrease due to the students who study in the building leaving for lunch. When lunch time is over, the cooling demand rises again until the end of the classes.

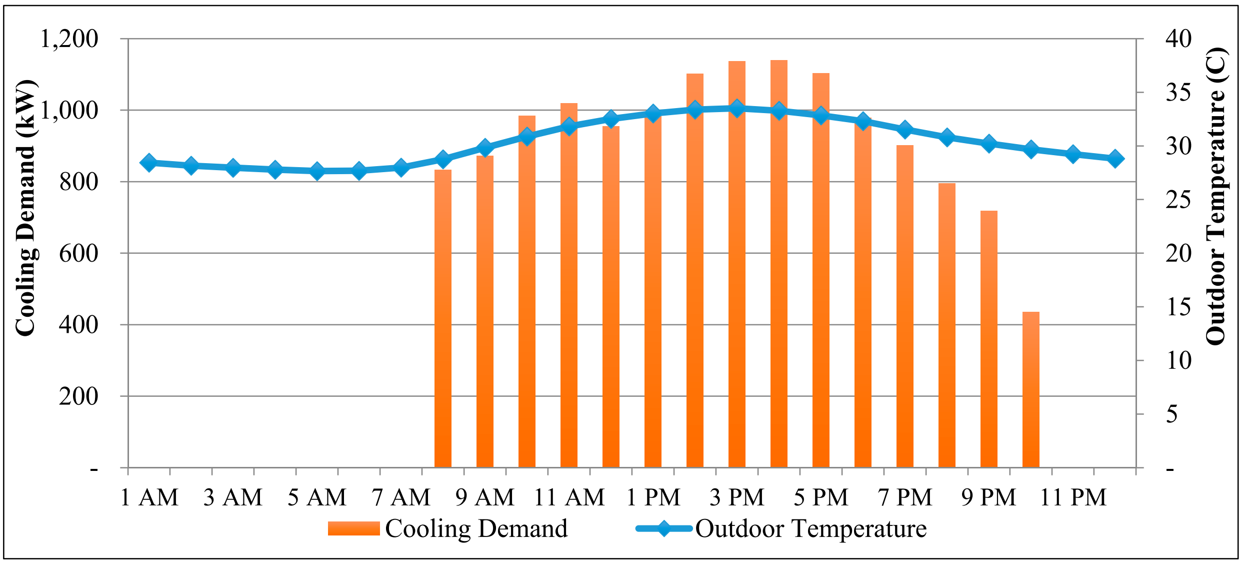

Figure 8. Cooling demand of the library building on the summer design day.

The hourly cooling loads of the building throughout the whole year were then carried out based on the annual weather data to determine the load distribution. As shown in Figure 9, the cooling load density during the winter period is relatively low compared to the summer period. The average hourly loads during winter periods are estimated at only 200 kW. The cooling load density from January to April is higher than from October to December. The majority of the cooling loads fall on the space interval between 250 kW and 500 kW. The extreme high load conditions, which is over 850 kW, only occur for several hours on the day with extreme hot outside temperatures or full occupancy, such as on the examination days.

3.3. System Performance Comparisons

Based on the previous cooling demand calculation, two equal sized, 850 kW water cooled or air cooled central chillers were selected to fit the building demand as a conventional cooling plan. The specifications of WCC and ACC were summarised in Table 6. Table 7 lists the detailed cooling hour distributions under full and partial load conditions.

Considering a chiller does not always run at 100% capacity, the performance of a chiller capable of capacity modulation while operating at various capacities should be determined, since it can affect energy use and operating costs throughout the lifetime of the cooling unit. For the conventional cooling systems, regression analysis was performed to plot a curve which can describe how the chillers' performance changes with the varied cooling loads, based on the partial load performance data of the cooling units provided by the manufacturer at rated standard conditions. Figure 10 illustrates the performance of specification of the water cooled and air cooled chillers. If Table 7 and Figure 10 are examined, it is obvious that the cooling systems are mainly working on their high performance interval, which is from 25% to 50% load ratio.

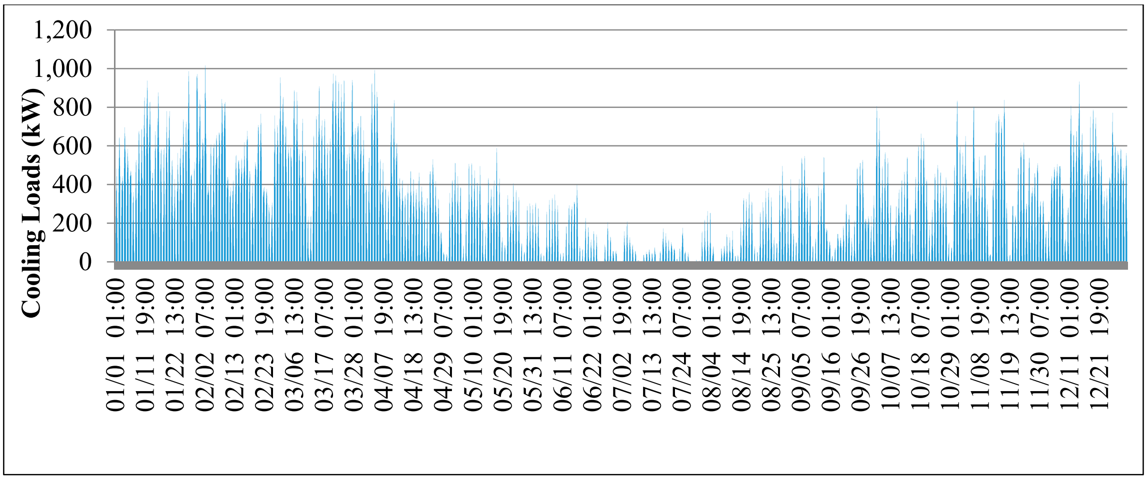

Figure 9. Hourly cooling loads of the library building throughout the whole year.

Table 6. Performance specification of the water cooled chiller and air cooled chiller.

Specifications	Water Cooled Chiller (WCC)	Air Cooled Chiller (ACC)
Capacity	850.0 kW	850.0 kW
Refrigerant	HFC 134a	HFC 134a
Compressors	Centrifugal	Centrifugal
Evaporator Entering Water Temperature	14.5 °C	14.5 °C
Evaporator Leaving Water Temperature	4.0 °C	4.0 °C
Condenser Entering Water Temperature	28.0 °C	-
Condenser Leaving Water Temperature	38.0 °C	-
Condenser Ambient Temperature	-	35.0°C

Table 7. Accumulative cooling hours under part load conditions.

Partial loads (%)	100%	75%	50%	25%
Cooling hours (h)	487	985	1448	2060

Different from the conventional cooling systems, the HSAC system was theoretically sized due to the relatively small cooling capacity of the lab-scale prototype. In order to fulfil the building's cooling demand, multiple HSACs were assumed with a total cooling capacity of 1200 kW.

To compare the energy consumption profile with the conventional chillers, the system performance of the HSAC was also required. However, because of the lack of availability of partial load performance data from its emerging market, the HSAC's laboratory performance data at different operating conditions were used. According to the working mechanism of HSAC, the system is more sensitive to the fluctuation of ambient temperature rather than the working conditions of a compressor. The compressor's output power is relatively stable most of the time while the additional pressure needs are fulfilled by the solar thermal collector. Thus, the ambient temperature was used to determine its COP instead of the partial load profile.

The dependence of COP from the ambient temperature was established, accounting for several assumptions which were: (a) the solar energy absorbed by the HSAC is constant during the day; (b) the temperature difference between the ambient temperature and the temperature of refrigerant leaving the condenser is stable at 3 °C [26]. Figure 11 demonstrates the performance changes of the HSAC with outdoor temperature.

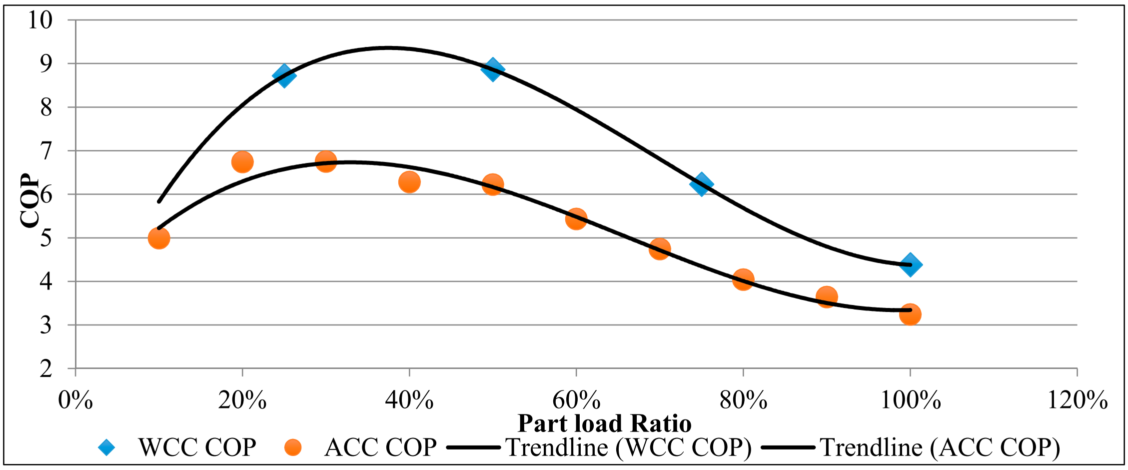

Figure 10. Performance of plant units under different part loads.

The polynomial function of the fitting curves can be established according to Equation (2):

$$y = a_0x^3 + a_1x^2 + a_2x + a_3 \tag{2}$$

where y is the dependent variable which is the Coefficient of Performance (COP) of cooling units; x is an explanatory variable representing the partial load ratio for conventional cooling equipment and the ambient temperature for HSAC; the coefficients a_0 to a_3 are constant values determined by curve-fitting of the manufacturer's data. The R^2 values of the function indicate good fit. The coefficients obtained from the regression are listed in Table 8.

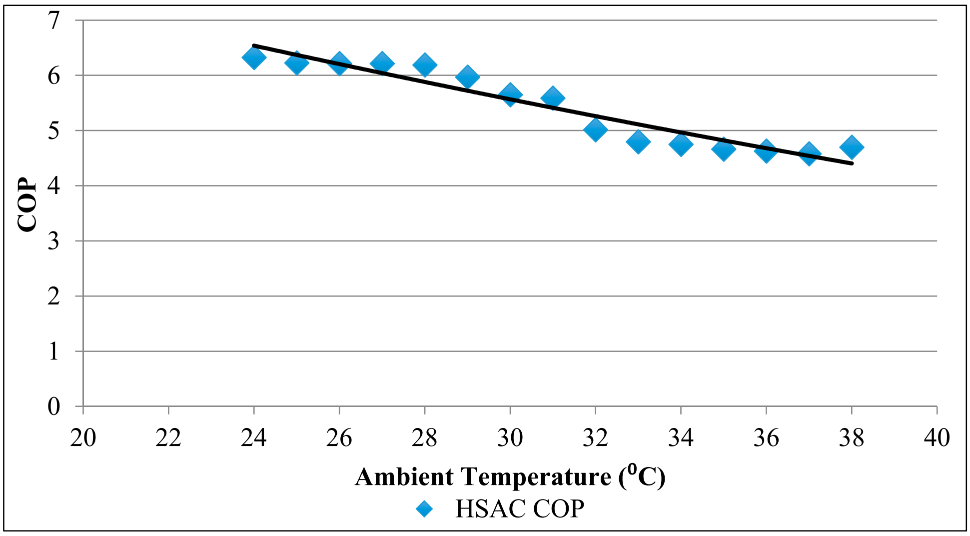

Figure 11. Performance of HSAC under different ambient temperatures.

With the three regression functions from Table 8, the variation in the Coefficient of Performance (COP) of each cooling unit during the entire year was calculated (Figure 12). It can be observed that the water cooled chiller has the highest COP which oscillates from 4.3 to 9.3, while the hybrid solar air conditioner exhibits slightly lower COP and fluctuates between 4.2 and 9.8, followed by the air cooled chiller with COP varying from 3.3 to 8.9. Although these three units have varied performances, they exhibit similar trends in the summer time. The units work at high efficiency in the early morning and late in the evening when the cooling loads are relatively low. As the cooling loads increase during daytime, the performance decreases for each unit. For example, the largest decrease in COP is predicted for 16:00 of the hottest day. Besides the extreme conditions, the HSAC exhibits a much more stable performance than the other two cooling units. During the Australian winter period from June to August, the trends become different. The COP of the HSAC increases because the ambient air temperature in winter is lower. Similarly for the WCC, the daily COP decreases significantly due to the lack of high part load running during daytime. However, in the hours of early morning and late evening, the cooling loads are very small, sometimes even below the manufacturer's recommended minimum cooling capacity limits. WCC and ACC were adjusted to ensure the units are not working below the limits. This explains the straight lines between the cooling periods from 13 June to 17 August.

Table 8. Constants used to determine the Coefficient of Performance (COP) values of the cooling systems.

Cooling Unit	a_0	a_1	a_2	a_3	R^2
WCC	37.867	−78.960	43.213	2.260	1.00
ACC	23.693	−46.786	23.074	3.362	0.973
HSAC	-	0.001	−0.227	11.295	0.914

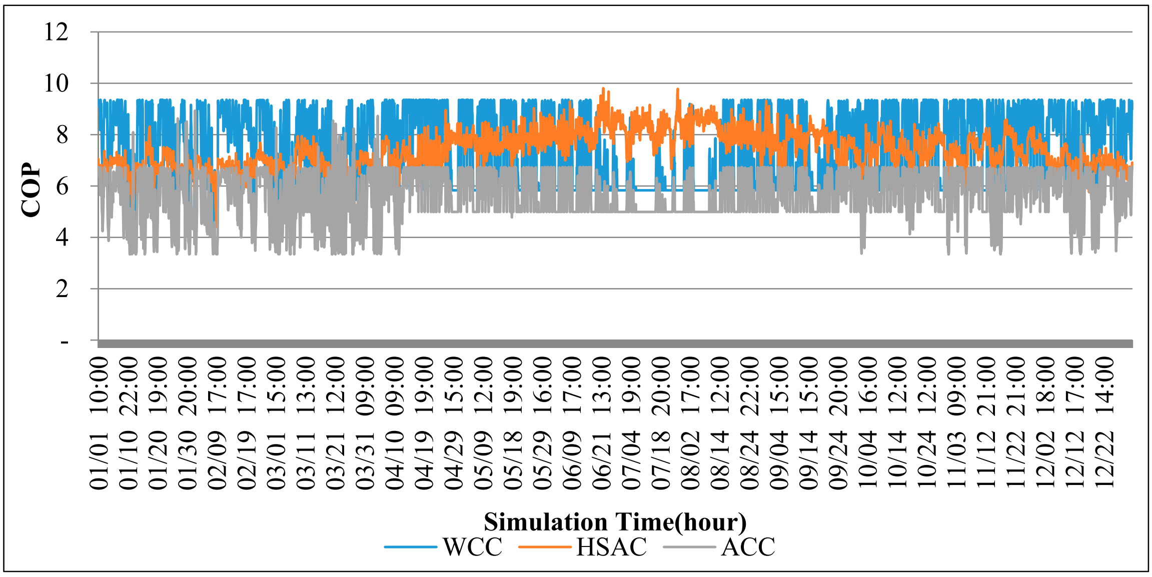

Figure 12. Hourly COP of the cooling units throughout the whole year.

3.4. Energy Consumption and Energy Saving Potential

Based on the cooling demand simulation and the cooling unit performance analysis, the energy consumption of these three systems were obtained and are shown in Figure 13. The results show that the ACC system needs more electricity to cool the building than the other two systems. The HSAC consumes more energy than the WCC in the summer time but is more economical in the winter periods. In total, the annual consumption of HSAC 212,564 kWh is significantly lower than ACC 266,186 kWh but slightly higher than that of WCC 198,855 kWh.

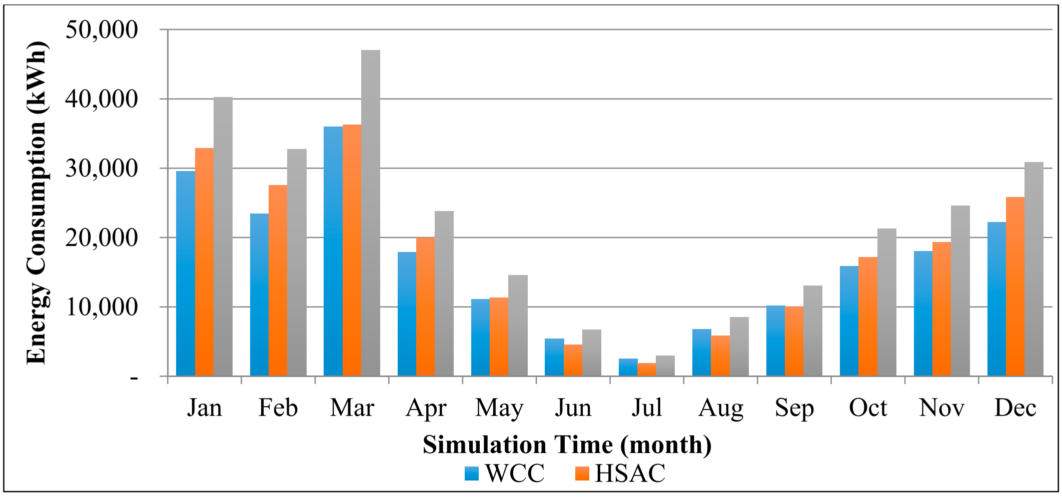

Figure 13. Monthly energy consumption results.

Accounting for the results from Table 5 and Figure 13, the energy consumption profile of the six scenarios are analysed and compared in Figure 14. Scenarios 1, 3 and 5 are the annual consumption of grid electricity of WCC, ACC and HSAC respectively, while 2, 4 and 6 are the ideal cases that apply PV electricity at the building's full PV installation capacity in order to substitute for the demand from the grid. The results presented here are in accordance with the previous research [27] and demonstrate the potential of the PV panel to not only cover all of the building's cooling electricity consumptions in Scenarios 2, 4 and 6, but can also have surplus electricity of 194,750 kWh, 127,420 kWh and 157,635 kWh respectively. Scenario 2, in which the water cooled chiller is integrated with PV panels in the building structure, provides the most energy efficient solution for cooling of the selected library building for the investigated yearly weather conditions in Sydney.

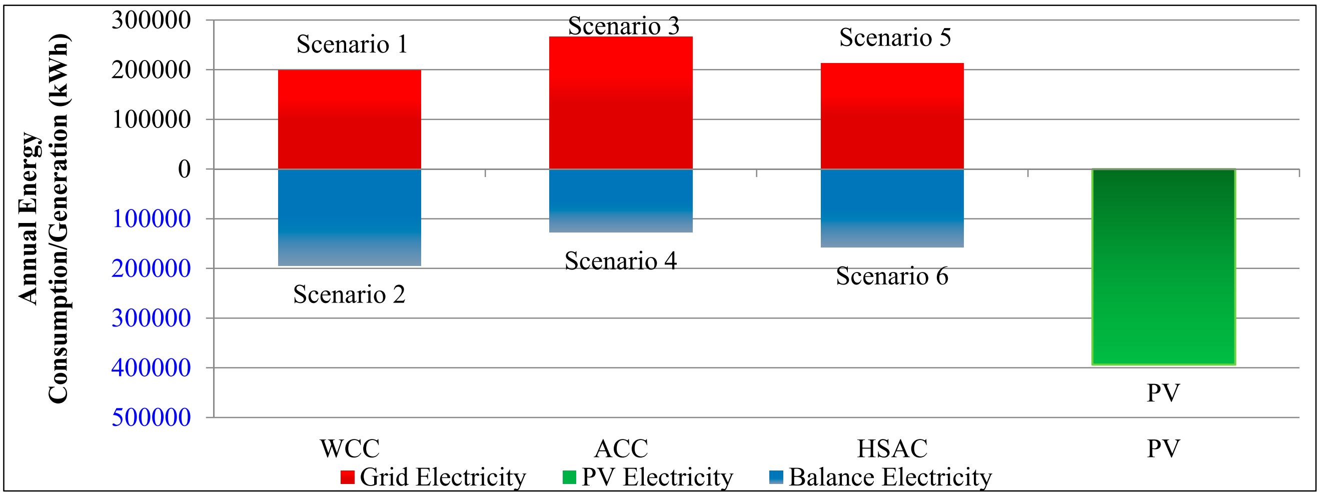

Figure 14. Comparison of annual electricity consumption and the energy structure among six scenarios.

3.5. Greenhouse Gas Emission Comparison for Cooling Systems

Based on Equation (1) and the annual energy consumption results from Figure 14, greenhouse gas emissions were compared between the six scenarios in Figure 15. For the cases without PV support, the cooling systems of the building emit more than 200 tonnes of greenhouse gases each year. However, the calculation results of scenarios 2, 4 and 6, indicate the PV technology can reduce greenhouse gas emissions effectively. The surplus renewable electricity has an equivalent of over 140 tonnes of CO_2 mitigation potential in the best case. However, it is important to emphasise that this calculation did not take into consideration the embodied energy and greenhouse gas emissions from production of the air-conditioning units and solar panels.

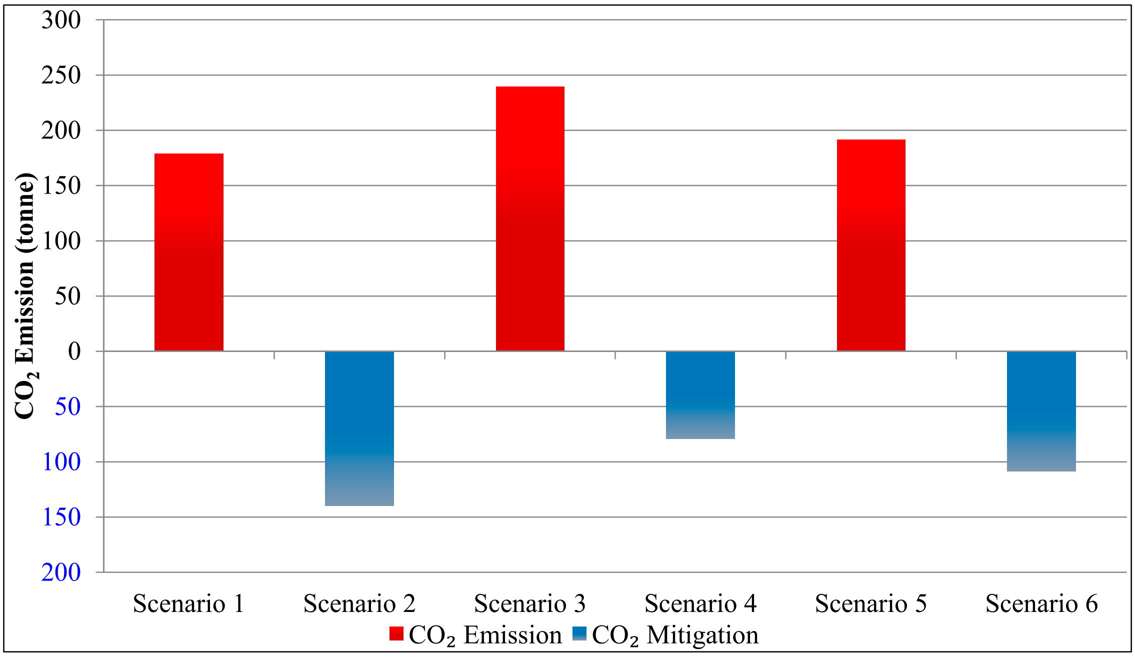

Figure 15. Comparison of annual greenhouse gas emissions among six scenarios.

4. Conclusions

This research evaluated three types of cooling systems in a complex educational building, including water cooled (WCC), air cooled chiller system (ACC) and hybrid solar air conditioning system (HSAC) for the cooling demand, power consumption requirements and greenhouse gas emissions based on the local weather conditions. To test the potential of the solar power used by the building, an annual cumulative insolation analysis was performed using a building model and accounting for the nearby shading elements. The cooling demand of the building throughout the whole year was then simulated. The findings of this research are as follows:

(1) The simulation results indicate that, under ideal conditions, if PV panels are installed on the investigated building, they will entirely cover for the annual electricity consumption for cooling of the building.
(2) The overall performance of the Hybrid Solar Air Conditioner (HSAC) is higher than the Air Cooled Chiller (ACC) but lower than the Water Cooled Chiller (WCC).
(3) The annual energy consumption of the HSAC was found to be lower than the ACC while it consumes more electricity than the WCC system. The BIPV technology can effectively reduce the electricity demand in the peak load period.

(4) Additionally, the greenhouse gas emissions caused by cooling the building could be completely offset by the use of renewable energy. The surplus electricity could be also used by other electronic appliances in the building to further mitigate the greenhouse gas emissions when the solar based PV technology is integrated in the building.

Although the BIPV technology is of great interest in the development of net zero-energy buildings, the initial cost of a full PV cell coverage is high, especially for the window area energy harvesting achieved by the transparent PV cells. However, this approach is expected to make more contributions in the near future with further reduction in its cost due to the rapid breakthrough of material developments as well as the manufacturing innovations.

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Author Contributions

Xiaofeng Li was responsible for the data collection, modelling and analytical part of this work. Xiaofeng Li provided the primary role of writing the paper. Vladimir Strezov helped with writing and revision of the paper and provided guidance, supervision, support.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

ACC	Air Cooled Chiller
BIPV	Building Integrated Photovoltaic
COP	Coefficient of Performance
GHG	Greenhouse Gas
GL	Ground Level
HSAC	Hybrid Solar Air Conditioner
LGL	Lower Ground Level
PV	Photovoltaic
R-value	Thermal Resistance Value
SHGC	Solar Heat Gain Coefficient
U-value	Overall Heat Transfer Co-Efficient
VLT	Visible Light Transmission
WCC	Water Cooled Chiller

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