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Review

A Literature Review of Naturally Ventilated Public Hospital Wards in Tropical Climate Countries for Thermal Comfort and Energy Saving Improvements

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Abstract: The tropical climate with its high average temperatures throughout the year affects the thermal comfort of buildings, especially for naturally ventilated spaces. The government's move to turn hospitals into green buildings is seen in line with the global commitment to conserve the environment and the country's current policy of supporting sustainable development. To achieve this goal, energy efficiency and thermal comfort need to be given priority in the focus on hospital planning and implementation for a better quality of the indoor environment. This literature review has led to the need to improve thermal comfort in natural ventilated wards in government hospitals. Some wards are built without air conditioning to save on construction costs, reduce utility costs through low energy consumption, as well as the need for infection control and airborne infections. However, current climate change requires a special study of thermal comfort in wards that use natural ventilation. An innovative solution is proposed to solve the problem statement identified in the reviewed literature through the application of solar PV/T systems and heat pumps. This hybrid system re-uses the heat energy (cogeneration) generated from solar PV panels to be cooled by heat pumps and is then pumped into the ward for cooling purposes. The proposed system has the potential to improve thermal comfort in natural ventilation wards and increase efficiency of the solar PV system for optimal electricity generation as well as improve the overall energy performance of buildings through low-energy cooling systems. It is not only solving the thermal comfort issue but also avoid the use of extra energy for cooling by optimizing the renewable energy.

Keywords: thermal comfort; building energy; naturally ventilated ward; hybrid system; tropical climate

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1. Introduction

Hospital buildings are more complex facilities compared to other buildings because they have specific clinical requirements that must be complied with to ensure the services provided to customers are met [1]. A hospital must be designed to have adequate ventilation and good air circulation to provide a comfortable space that complies with indoor environmental quality (IEQ) requirements [2,3]. This is very important in controlling any infection and contamination in the clinical area while maintaining a clean environment. To meet the established clinical needs, the design of a building must have a combination of sustainable architecture and engineering. One of the ways to achieve this is through green building initiatives.

The rating and certification of green buildings developed around the world is intended to guide architects, engineers, contractors and building owners to conserve the environment through established methods and guidelines. Green buildings not only fulfill the function of a building in providing excellent service but also ensure that they comply with all applicable local and international laws, regulations, standards, and procedures that support the operation of a hospital. In addition, the implementation of each green element in the hospital building will help reduce operating costs through energy and water savings as well as more efficient and efficient use of green technology. In many developed countries, the building sector became one of the largest energy consumers compared to other sectors such as industry and transportation. For example, the total primary energy demand of the building sector in China constantly increased, from 24.1% in 1996 to 27.5% in 2001 and is predicted to continue to increase by 35% in 2020 [4,5]. Globally, the primary energy demand of building sector represents about 40% of the total, which contributes to more than 30% of carbon emission reduction [6]. This situation has prompted various studies worldwide to improve building energy performance especially in building envelope design and construction improvement [7–10].

Sustainable buildings should also provide comfort to homeowners through the preservation of indoor environmental quality, which is one of the key elements in green building implementation. However, the comfort of the occupants in the building is rarely taken into account, especially in modern hospital buildings that have long since been erected because the original design that does not fully take into account the concept of sustainability as well as climate change, which are major issues today. While all building owners focus on energy savings to reduce operating costs, not many views thermal comfort as a major issue. A previous study found that the thermal comfort is more important than other indoor environmental condition. Building occupants ranked the thermal comfort above indoor air, visual, and acoustic quality which requires more attention to improve the building indoor environment [11]. In the context of hospitals, the provision of air-conditioned wards or use of natural ventilation is aimed at reducing construction costs and operating costs while providing access to low-income people receiving in-hospital care. Although thermal comfort has not been a major factor in the construction of hospitals in the past, it is now necessary to revisit the issue of climate change. Accordingly, there is a need for a solution to improve the thermal comfort of natural ventilation wards to provide comfort to the occupants of the building especially patients receiving treatment as well as the low-energy use of the method or system they wish to apply.

This paper deals with naturally ventilated ward and associated issues involving public hospitals. The review covered important aspects of a naturally ventilated ward in the Malaysian public hospital context including climate, energy management, and thermal comfort. Following the review, future research areas are identified for potential solutions to the problem statement revealed in the reviewed literature. This paper is organized in nine sections as follows. Section 2 provides background information about existing sustainable programs in Malaysian public hospitals. It is followed by a review of naturally ventilated wards in hospitals in Section 3. The important aspects of naturally ventilated wards such as climate, energy management, and thermal comfort including associated issues involving public hospitals are reviewed in Sections 4–6, respectively. Lastly, a potential solution to close the gap identified in the literature review is discussed in Section 7 followed by the discussion and conclusions in Sections 8 and 9.

2. Sustainable Program in Malaysian Public Hospital

Energy efficiency and environmental conservation are of paramount importance to the Malaysian government. Among all the government building infrastructure, hospitals have been identified as one of the highest use facilities in terms of electricity. Higher education institutions including universities are the other major users of high-power electricity for government buildings [12].

The Ministry of Health Malaysia (MOH) implemented various energy saving initiatives to achieve its goals toward green building and sustainable health facilities. Efficient energy management is one of the key agendas of the ministry, which not only saves electricity consumption but also reduces the cost of hospital management utilities, replaces obsolete government assets that no longer operates optimally, reduces fire risk, and protects the environment. This is in line with government aims to reduce carbon emissions by 40% by 2020 based on the gross domestic product of 2005 [13] and the target of 45% by 2030 [14].

The MOH has commenced implementation of sustainable program at all government hospitals since 2015 under the Hospital Support Services Concession Agreement. The program includes green building, energy management, indoor air quality (IAQ), and recycling (3R) activities which contribute toward sustainable healthcare facilities to continue to reduce carbon emissions and reduce the impact of climate change [15]. Under this program, MOH has been a prime example in the public sector and has been a leader in implementing sustainable strategies and initiatives toward green building certification in the country.

Through this program, MOH successfully achieved its energy saving goals and has seen many achievements since the introduction of the 'Safe and Green Toward Smart Healthcare Facilities' policy which supports initiatives in green facilities in the management of Ministry facilities [16]. These policies are outlined in the MOH's sustainable framework as shown in Figure 1. The implementation of energy management and energy projects showed significant changes in the amount of energy use and positive impact in reducing carbon emissions in Government hospitals [1]. Energy management is one of the key aspects that should be given attention in achieving green building rating and is particularly suited to high-energy hospital buildings in its day-to-day operations to deliver the best services to the people. As of 2018, MOH has achieved RM65 million in energy savings compared to 2015 and 2016, equivalent to 164 GWh and a reduction of 106,000 tonnes of carbon dioxide (CO_2) carbon emissions [17].

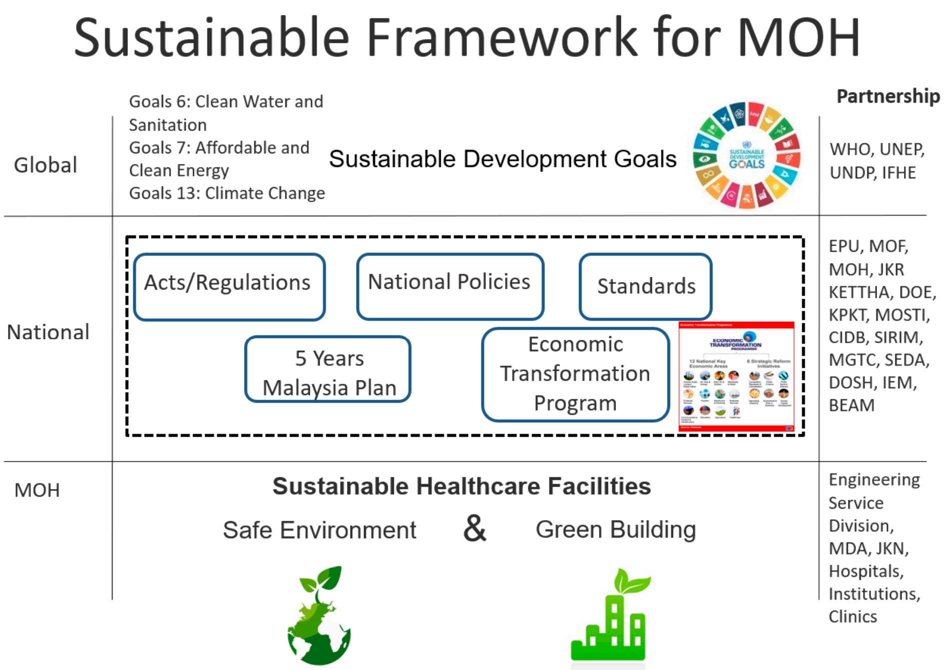

Figure 1. Sustainable framework for government hospital [1].

MOH is a ministry that has always supported government initiatives by implementing energy efficiency and renewable energy programs. The hospital's energy saving activities began with a cost-free initiative that required the involvement of hospital staff and users in implementing an efficient energy management system. Furthermore, low-cost and high-cost energy initiatives are being implemented on the proposed energy activities to generate more energy efficient savings using government green procurement (GGP) technology. Green technology has always been a priority and has been a catalyst in MOH energy projects and activities to drive and support green growth in the country. The use of green technology in MOH hospitals such as LED lighting, oil-free magnetic bearing and solar absorption chiller has been able to provide optimum energy savings and environmental protection through the introduction of energy efficient equipment and environmentally friendly products that enhance the overall performance and capabilities of the building [17].

Energy management is strongly emphasized in every aspect of sustainable programs and green building at MOH level. While it clearly benefits ministries and hospitals, there is much that can be improved on to achieve green building status. Undeniably, energy efficiency is one of the most contributing factors in most green building rating tools [18]. However, other elements especially IEQ should be given equal importance especially to hospital buildings where the main client is a patient in need for treatment.

3. Naturally Ventilated Ward

The hospital is a complex building with a wide range of engineering systems and high-tech medical equipment delivering services to patients. Most hospital spaces have specific clinical needs and require compliance with applicable laws and regulations to control for any infections and contamination in the internal environment. Good ventilation in hospital buildings is very important and is the main focus in designing hospitals. In addition to protecting patients, staff, and visitors from contaminated air and hazards, good ventilation also provides thermal comfort to the occupants of the building [19].

Yau et al. [20] reviewed several studies on ventilation in hospital buildings and provided the latest relevant information for researchers' reference. According to the authors, the main purpose of good ventilation in the occupied space is to provide fresh air to the occupants and to remove the heat generated by the space. Studies also showed that improvements in ventilation and layout in hospital design can provide better health for patients and provide a good working environment for staff on duty [21]. The basic principles of ward design are focused on ventilation, lighting, and hygiene [22,23]. The internal environment of the ward should focus on the needs of the patients and staff [24].

Natural ventilation is a commonly used method for providing high airflow rates with low energy consumption. Tropical climates such as those in Malaysia and Singapore also adopt natural ventilation as a low-cost option in building design. In essence, natural ventilation is the circulation of air that moves the outside air into the building through natural force. Movement is dependent on the design of the building and the external climate compared to the interior environment. However, the difficulty of maintaining a constant negative pressure, as it is always dependent on the external climate, is a challenge. The latest technology and advancements with the help of mechanical systems and other control systems have made natural ventilation an attractive option to apply especially in the construction of high-cost health facilities. In relation to economic benefit, the previous study by Yuan et al. [25] found that the installation of mechanical ventilation is cheaper when there is no indoor emission provided that the filtration efficiency and envelope air tightness are complied with the required standard.

The World Health Organization (WHO) has proposed the minimum ventilation rate required to prevent any spread of airborne infections. The minimum ventilation rate is described in more detail in Table 1. Adequate ventilation is very important for patient care areas including in wards. According to a study conducted by Escombe et al. [26], they found that the risk of airborne infection was higher in areas where mechanical ventilation was compared to natural ventilation. Qian et al. [27] also conducted a study on natural ventilated wards in Hong Kong's national hospital buildings. The results show that ventilation rates of 18 air changes per hour (ACH) and 24 ACH have the potential to reduce the risk of airborne infections in the ward. However, health facilities that use natural ventilation should ensure that the design of the building is correct and that the required ventilation rate is fully adhered to. This is to prevent thermal discomfort other than the possibility of airborne infections among patients and occupants of hospitals.

Table 1. Minimum rate of natural ventilation according to WHO guidelines [28].

Type of Room	Average Minimum Hourly Rate of Natural Ventilation (Litter/Second)	Statement
Normal ward	60 l/s every patient	Applies to other health care areas such as the corridor where emergency cases occur
Airborne precaution rooms	160 l/s every patient	Applies only to new facilities and major renovations
Corridor	2.5 l/s every m^3	For spaces that do not have a fixed number of patients

The thermal comfort of wards designed using natural ventilation needs to be reviewed at this time in light of the climate change issues that are frequently discussed in each forum. Improvements in thermal comfort in wards in MOH hospitals will help hospital staff work in a conducive environment for productivity and at the same time provide comfortable conditions for patients to seek treatment. It is advisable that thermal comfort in natural ventilated spaces in health facilities such as wards is improved using a sustainable, energy efficient and cost-effective method to provide a conducive environment for the occupants of the building, especially patients seeking treatment and in the recovery phase.

4. Climate

4.1. Tropical Climate

The tropics are a terrestrial area located at latitude 23.5 degrees north and south of the equator. Typically, temperatures in the tropics are above 18 °C with high rainfall throughout the year. According to Yau et al. [20], a tropical climate is divided into tropical monsoons, tropical savannas and tropical rainforests that are distinguished by the amount of rainfall distribution. The warmer climate of the year is also due to the low latitude tropical regions and only slight solar fluctuations. The intense sunlight gives the nations of the region the opportunity to use solar energy as an alternative to daily applications. Figure 2 shows a world map of tropical climate regions with three subtypes which are tropical rainforest (Af), tropical monsoon (Am) and tropical savanna (Aw).

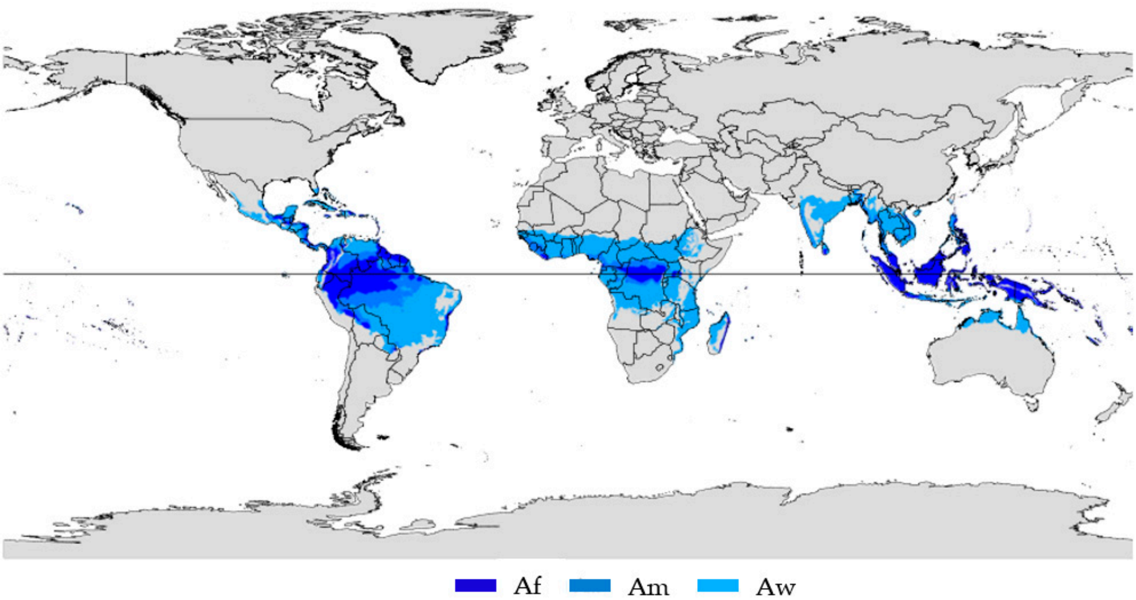

Figure 2. Tropical climate region [29].

Weather conditions outside the tropics and current climate change are very important factors in considering the use of fresh air into buildings. It also indirectly affects the selection of equipment and system sizes designed for ventilation and air conditioning purposes. In addition, the need for thermal comfort for the people living in the tropics should be taken into account in balancing energy use requirements for cooling and environmental protection. In previous study, the most energy usage for space cooling in the buildings are involved the countries in low latitude regions which experienced warmer climates [30]. This is due to the high use of electricity for cooling activities to provide thermal comfort as opposed to the concept of sustainability.

4.2. Malaysia Climate

The climate in tropical rainforests is generally warm and humid throughout the year with an average rainfall of at least 50 mm (2 inches) per month [31]. There is no dry season in tropical rainforests compared to other tropical climates. The characteristics of this country are consistent and uniform temperatures, with high humidity and abundant rainfall throughout the year. Malaysia is one of the countries in the tropical rainforest located along the equator with latitudes of 1 to 7 degrees north and longitude of 100 to 120 degrees to the east.

According to Mekhilef et al. [32], Malaysia receives large amounts of sunlight based on its geographical location and high solar radiation throughout the year averaging 400–600 MJ/m^2 per month. Bayan Lepas and Kota Kinabalu recorded the highest annual average solar radiation compared to other major cities in Malaysia; it is more than 1800 kWh/m^2 [32]. The average sunshine was also recorded, ranging from four to eight hours a month or around 2200 h of sunshine a year [33]. High solar radiation will lead to an increase in sol-water temperature which in turn results in a high temperature difference between the exterior and interior surfaces of the building [34]. This will increase the cooling requirements of the building due to the increased amount of heat generated.

Understanding Malaysia's climate is crucial in designing buildings that respond to and adapt to current weather conditions. The information of Malaysia's climate condition could also benefit the ASEAN country in the region that have same weather characteristics. A study conducted by Tang [35] shows that annual average temperatures, incidence of extreme weather changes and sea level in Malaysia will continue to rise while rainfall distribution is volatile and constantly changing. However, knowledge of solar radiation is also very important compared to others as the amount of heat transferred into the building can be determined by the data obtained [36]. To maintain the building's thermal comfort, a variety of active and passive systems are introduced either through the design of the building or using the latest technology applications.

It can be concluded that the global climate change has affected the built environment. It is also supported by previous studies where heat stress is in an increasing trend during the 20th and 21st centuries [37–39]. This trend will lead to more space cooling demand and would result in additional energy use in the building. Thus, it is important to find the best way to propose new technologies or innovations that can provide space cooling with efficient use of energy. Solar-powered cooling may be a good solution in term of energy saving in hot climates due to availability of maximum solar intensity and building peak cooling load are about at the same time [40–42].

5. Energy Management

5.1. Energy Efficiency

Energy efficiency can be achieved by an organization through systematic and comprehensive energy management implemented on daily operations and maintenance activities. For hospital buildings, a good energy management system can identify potential energy savings through energy audits and subsequently help building owners plan appropriate activities to improve the overall performance of the building. It is a continuous process involving all parties whose result is efficient use of energy that will reduce the cost of building management operations and indirectly help to protect the environment. However, the lack of information on the performance of energy consumption in government hospitals and benchmarking as a reference to energy savings targets makes planning and implementation difficult [43].

There are many elements to consider in the energy audit process before any potential energy savings can be suggested. Some of the important elements that need to be studied are the load distribution pattern and the variety of electricity usage in hospitals. In general, government hospitals can be divided into several categories by number of specialties and vary by size and design. These features make it unique and energy use is based on several factors, such as the amount of assets and equipment it has, the age of the building and the performance of the engineering system, the number of beds, the floor area, the air-conditioned area as well as the passive and active design of the building. energy efficient. Energy consumption can also change drastically throughout the building's operation due to the additional load demand, which is highly dependent on the changes in the elements and parameters discussed. In this regard, it is important for building owners to gather information that will help identify key electrical consumers in hospitals leading to energy savings opportunities [44].

Energy savings and cost reduction on electricity bills are a major challenge for building owners due to the high-energy consumption and increasing hospitalization. A study on the use of energy in hospitals showed that about 40% of total electricity consumption comes from refrigeration and air conditioning systems [45]. The main source of energy used to operate all these systems is through electricity which accounts for 75% of the total energy consumption. A study conducted in 2014 to analyze energy distribution patterns in the same hospital found that the average annual electricity consumption was more than 40,000.00 kWh. This number represents 63% of the energy used by the air conditioning system and 17% of the energy is from the lighting [46]. Another example of the study of energy consumption in hospitals was conducted in 2010 where 36% of energy consumption came from lighting and 34% of energy consumed by medical equipment [47]. The total energy consumption for hospital buildings in the study showed that approximately 19,000,000 kWh of electricity was used. The results of these studies show that electricity consumption is very high for the purpose of lighting and cooling the space to provide thermal comfort to staff, patients, and occupants of buildings in health facilities.

Generally, the cooling system and air conditioning system are not only the most used energy in hospitals but also in other buildings. A study conducted on institutional buildings yielded a similar result in which refrigeration systems and accessories primarily account for about 51% of total building energy use [48]. While almost every building owner chooses to replace or upgrade their cooling system to a more energy efficient system through retrofit methods, it does not guarantee the best investment solution due to its high cost and long return. Further research to find alternatives should be undertaken to determine the best energy initiatives that can be implemented in hospital buildings to provide high-energy savings to building owners as well as cost-effective and more cost-effective implementation of the government.

Sustainable energy management systems are capable of planning low, medium, and high-cost long-term energy activities. Techno-economic evaluation is the best way to get a sense of the suitability of implementing measures to improve high-cost energy performance before it is finalized. However, priority should be given to low and medium cost measures such as training and awareness campaigns, sustainable practices in building operations and maintenance as well as considering passive systems in buildings through building cover repair and the use of new technologies. Passive design strategies such as the use of daylight, reducing heat entry, and natural ventilation are very effective methods of reducing overall energy consumption in buildings [49]. In addition to energy savings, the comfort of building occupants and minimizing the negative impact on the environment is a key goal in energy efficient activities [50].

In ensuring that new buildings in Malaysia are built with energy efficient elements, a standard was developed by the Department of Standards Malaysia (DSM) as a guide and reference to stakeholders. The MS1525 Code of Practice has been in existence since 2001 with several subsequent improvements with the latest version being in 2019. Generally, this practice code was developed for non-residential buildings for the implementation of energy efficiency practices and renewable energy use to achieve building energy intensity (BEI) which is proposed not to exceed 180 kWh/m^2/year [51]. To date, some states adopted this code of practice as part of the compliance requirements in the Uniform Building Code (UBBL) under clause 38 (building energy intensity). Based on the code of practice, the construction of new buildings and renovations should take into account the energy efficiency and renewable energy requirements set forth below:

1. Buildings with air-conditioned areas exceeding 4000 square meters shall perform the following:
    a. Designs must comply with MS1525 Code of Practice with Overall Heat Transfer Value (OTTV) not exceeding 50 W/m^2 and Roof Heat Transfer Value (RTTV) not exceeding 25 W/m^2;
    b. Provide energy management system for monitoring purposes.
2. The heat transfer value (U-value) of the entire roof of the building shall not exceed:
    a. 0.4 W/m^{2}K for roof weight less than 50 kg/m^2;
    b. 0.6 W/m^{2}K for roof weight exceeding 50 kg/m^2.

Although there is no specific requirement for U-value of walls and windows, the lower heat transfer value used in the building design will help in achieving the OTTV value that has been set in the regulation. Therefore, heat transfer plays a very important role in making a building energy efficient. The building envelope should be in perfect condition to ensure that heat transfer from the outside to the building is minimized. Air conditioners require higher energy use to cool off a lot of accumulated heat compared to buildings with good insulation on the entire building cover. The use of insulating material to a certain thickness can reduce energy consumption in hospitals operating 24 h a day [52]. Thermal performance can also be improved by considering passive wall systems that also reduce electricity consumption [53].

5.2. Renewable Energy

Energy demand has increased dramatically by 52.98% which is equivalent to 62,488 ktoe in 2017 compared to only 40,846 ktoe in 2009 [54]. The total installed electricity generation capacity in the Peninsula has not changed much since 2009 at around 21,000 to 22,000 mega-watts (MW) [55–58]. Data released by the Energy Commission in 2016 support this statement that current capacity stood at 20,944 MW and 20,710 MW in 2014 and 2015, respectively. In 2016, energy demand exceeded 17,000 MW and showed a significant reduction in energy reserves from over 40% in 2010 to just about 25% today [59]. If energy demand continues to grow, plans for energy generation need to be implemented immediately to meet those needs.

Changes in energy policy and the use of solar energy, which is better than other renewable energy sources, opened up more initiatives introduced to generate electricity from these sources. Between 2011 and 2016, increasing demand for Feed-in Tariff (FiT) schemes has successfully reduced the cost of PV systems by 23% from RM9000/kW to RM6900/kW [60]. This reduction in costs has led to many solar farms being opened across the country with each property owner signing a 21-year power purchase agreement with Tenaga Nasional Berhad (TNB) under the FiT scheme at between 80 cents and 90 cents per kWh [61,62].

In 2017, electricity generation via PV under the FiT scheme reached up to 314 MW [63]. Energy generation is expected to continue as the government introduces the implementation of a large-scale solar PV plant (LSSPV) with a target of 200 MW annually from 2017 to 2020. In early 2016, the government also introduced the concept of net energy metering (Net Energy Metering (NEM)). as a complement to the FiT scheme which is seen to have matured. Previously, electricity production under the FiT scheme for domestic consumers was channeled to the grid for sale. However, the government is of the view that it is best to use the energy first by consumers before selling it to energy suppliers. NEM was introduced to replace the FiT scheme in 2018 and in 2019 the excess energy is no longer sold but every 1 kWh of energy exported to the grid will be counter to the 1 kWh of energy consumed from the grid at the tariff rate [64]. The main purpose of NEM model is to generate electricity from renewable energy for its own use which will reduce energy demand from the grid at peak hours.

In summary, the implementation of energy saving measures, renewable energy initiatives including energy conversion technologies are part of the climate change mitigation actions which can also have a positive impact on social and economic aspects [65]. Renewable energy is seen as a current choice for building owners and energy suppliers by taking into account the country's existing policies and directions in energy generation and global commitment to reducing carbon emissions into the environment. Hospital buildings can implement these innovative energy initiatives as a means of reducing reliance on electricity from the grid while at the same time reducing high monthly utility costs to cover 24-h operation and increasing equipment to meet clinical needs. The energy generated is also from a clean source and very suitable with the Malaysian climate which has a high average solar radiation throughout the year and has the potential for the implementation of solar PV systems in hospital buildings. More studies need to be conducted to explore the potential of integrated approach to the use of solar energy [66,67].

6. Thermal Comfort

Thermal comfort is an expression of state of mind that deal with thermal environment satisfaction. This condition is subjectively evaluated using ANSI/ASHRAE Standard 55 [68]. Thermal comfort should be measured to determine the level of individual heat sensation which is also influenced by climate and environmental factors. Usually a mathematical model is used in the calculation of thermal comfort to represent all the relevant elements. Various thermal comfort indices have been developed from simple linear equations to complex algorithms to connect individual thermal sensations with the environment. Questionnaires on thermal comfort condition were also conducted on individuals to get a comparison between the survey result with the mathematical models used because the results of studies that come from individuals alone are inconsistent and heavily influenced by other factors.

6.1. Patient Thermal Comfort

Factors of climate change and hot temperatures throughout the year in Malaysia make thermal comfort an important issue for indoor air-conditioned buildings. Many studies were conducted on the improvement of thermal comfort through the implementation of an active and passive system to provide comfort to the occupants of the building besides being a requirement for the rating of green buildings. In contrast to the hospital, the occupants of the building consist of a diverse group of patients, visitors, and staff on duty. The degree of thermal comfort for all of these groups may vary due to factors such as sensitivity to climate change by individual, length of time in the building and the number of people in one space at a time.

Chua et al. [69] reported that electricity consumed 60% of the total energy used in buildings for cooling purposes. Therefore, various methods were used to reduce the use of electricity to provide thermal comfort including designing buildings using natural ventilation in several spaces [70]. However, not many studies on thermal comfort have been done for hospitals in tropical and very few areas involving hospitals in Malaysia, especially in government-owned hospital buildings. The study conducted by Lan et al. [71] through building models and simulations, proposes several passive and natural ventilation methods to improve thermal comfort in tropical Singapore hospital wards. However, the results obtained are based on simulation alone and do not involve any retrofit work. Generally, natural ventilation is an excellent approach to energy efficiency, but it needs to be re-examined due to the ongoing climate change as well as the design of older buildings that require special attention to existing building cover enhancements.

The thermal comfort of the patients was studied in various ways to capture the thermal sensation experienced by each individual seeking treatment and living in a hospital ward. Hwang et al. [72] concluded that physical strength strongly influences an individual's heat sensation in a field study conducted at a university hospital in Taiwan. However, the factors of age, gender and adaptation to climate change have no effect on the patient's heat sensation. In another study, patients expected lower environmental conditions than neutral thermal comfort levels [73]. Temperature conditions in the ward were also studied at the National University Hospital of Malaysia (HUKM) by [74]. The results of this study found that the level of thermal comfort during the day was slightly cold and cold while the night conditions were very cold. The authors conclude in the study that the daytime neutral temperature is around 26 °C with a range of thermal comfort between 25 °C and 27.7 °C. While the acceptable thermal comfort range is 23.8 °C to 29 °C. Ormandy and Ezratty [75] studied several groups of patients who are susceptible to high temperatures based on the thermal comfort range outlined by the World Health Organization (WHO). Patients with chronic diseases such as cardiovascular, diabetes, respiratory problems, kidney patients, Alzheimer's and Parkinson's are at high risk of exposure to high space conditions. From past studies, it is clear that the thermal comfort experienced by patients varies based on a variety of factors.

6.2. Staff Thermal Comfort

The ability of individuals to respond to weather and temperature varies. In addition to the thermal comfort of the patients discussed earlier, a literature review was also conducted on hospital staff. In contrast to patients who may stay in the ward for several days, hospital staff only stay in the ward for a few hours a day depending on the designated working hours. This study is important to provide an appropriate approach to provide thermal comfort to these two groups of staff and hospital patients.

Field studies conducted in tropical Thai national hospitals found that the temperature ranges accepted by patients and staff were 21.8 °C to 27.9 °C and 24.1 °C to 25.6 °C, respectively [76]. This indicates that the patient has a greater temperature range than the hospital staff. However, the study was focused on air-conditioned space only. Another study involved 114 medical staff in Malaysian hospitals and found that higher temperatures were required for thermal comfort than the temperature criteria set in ASHRAE standards in 2003 [77]. The neutral temperature for hospitals in Malaysia according to the study was 26.4 °C while the temperature range for satisfactory thermal comfort hampered 90% of the occupants ranging from 25.3 °C to 28.2 °C.

In addition, a study in Japanese hospitals showed that 64.5% of hospital staff surveyed felt slightly hot, hot, and very hot based on their respective levels of thermal comfort [78]. Patients only achieved 22.3% of the same level of thermal comfort. The study was conducted on 36 patients and 45 hospital staff with a mean study temperature of between 20 °C and 23 °C and a low humidity of less than 40%. The conclusion made in this study was that hospital staff experienced warmer thermal comfort than patients. Khodakarami and Knight [79] also conducted a study on patients and staff at four hospitals in Iran. The study found that the staff felt very hot and uncomfortable in the temperature range between 20 °C to 28 °C if the air speed was between 0.1 m/s to 0.5 m/s and the current humidity was between 30% and 60%. A study of the actual mean vote (AMV) by Ottenheijm et al. [80] also supported that employees experience thermal comfort problems compared to patients under the same thermal environment. A total of 160 hospital staff and 65 patients were involved in the study. Based on these studies, overall hospital staff showed poor thermal comfort compared to patients. Hospital staff may be in a different state of thermal comfort elsewhere before entering the hospital room for work. Adapting and accepting the thermal comfort of different hospital staff with patients should help researchers find the right temperature range for both groups.

Thermal comfort for patients and staff in hospital ward is always given priority as both groups are equally important. Finding the balance between thermal comfort improvement and energy efficiency are quite hard due to the use of energy required for space cooling to satisfy building occupants individual thermal requirement. As for naturally ventilated wards, the cooling loads are much depend on ambient condition and future climate scenarios. Therefore, the application of co-generation or tri-generation in heating and air conditioning system should be explored as the system could provide high energy saving and more CO_2 reduction [81–83].

7. Thermal Comfort and Energy Saving Improvement

Research gaps obtained from the literature review found that thermal comfort in naturally ventilated wards in public hospitals needs to be improved to provide a favorable environment and comfort for patients and staff in the building. However, the best solution should be identified to improve thermal comfort through space cooling due to weather factors in tropical climates while maintaining current electricity consumption and using renewable energy. This step is very important to support the government's aspiration in achieving green building certification, compliance with existing energy policies, saving on operating costs, conserving the environment, and providing a conducive hospital environment. Therefore, the proposed system as a potential solution to problem statement should include the improvement of thermal comfort in the naturally ventilated ward, using low energy consumption as well as renewable energy application. Table 2 shows the current system and strategies adopted to improve the indoor thermal comfort and important information regarding space cooling, energy consumption and use of renewable energy.

Table 2. System and strategy adopted to improve thermal comfort.

System/Strategy	Improve Thermal Comfort	Provide Space Cooling	Low Energy Consumption	Use Renewable Energy
Passive design strategies [20,71,84–86]	√	×	√	×
Ceiling fan [87]	√	×	√	×
Air conditioning unit [88]	√	√	×	×
PV/T and heat pump [41,82,89,90]	√	√	√	√
PV and heat pump [91–94]	√	√	√	√
Solar thermal and heat pump [95–97]	√	×	×	√

Based on the table provided, it can be concluded that the PV/T heat pump system and PV heat pump system meet all the criteria needed by the public hospital ward for thermal comfort and energy saving improvement as well as using renewable energy in the system application. Thus, the systems are discussed further in the next section.

7.1. Photovoltaic/Thermal (PV/T) System

Solar PV has attracted a diverse group of stakeholders including researchers, industry groups including manufacturers and suppliers, government and private sectors and environmental activists for producing clean, environmentally friendly, and economically viable products in the long run [98]. According to the record, solar PV usage has increased year-on-year from 3.7 GigaWatt (GW) to 177 GW from 2004 to 2014 [99]. However, only 16% of renewable energy is used for cooling and space heating [100]. Sunshine and high temperatures throughout the year are two important factors that influence PV in generating electricity according to [101].

According to a study conducted by Agrawal and Tiwari [102], the efficiency of PV panels in generating electricity from solar power is between 12% and 18% and about 80% of the solar energy is either rebalanced or converted to heat energy. This is also supported by Luque and Hegedus [103] in their paper in which PV cells produce only 6% to 25% of electricity under optimal operating conditions and the semiconductor materials used also influence the amount of energy produced. The main drawback of the current PV module is that it can reach temperatures up to 40 °C which is above the ambient temperature. This would result in a decrease in the power output of 0.2% to 0.5% for every 1 °C increase in PV module using crystalline silicon cells [104]. This was also studied by Chow et al. [105] where each increase in temperature of 10 °C reduced the efficiency of the PV panel by 5%. In addition, previous studies have shown that the efficiency of PV panels can also be influenced by the reduction of open-circuit voltage in high temperature systems [106–109].

Therefore, it is very important to reduce the heat generated by the PV panels to obtain high system efficiency for optimum electricity generation. In the context of MOH hospitals, the production of optimum electricity through the solar PV system can help reduce the day-to-day operating costs and provide long-term benefits in terms of overall life cycle costs. Based on previous research by some researchers on heat removal methods, it can be concluded that water and air are some of the elements used for PV panel cooling purposes. However, the evolvement of heat collector technology through previous studies have improved the thermal performance of solar collectors [110–112]. Today's technology has adopted the concept of hybrid PV and heat collectors as a cooling system or better known as PV/T. The hybrid system is able to collect heat energy generated for other purposes such as hot water production and space heating while also fulfilling its main purpose of enhancing the efficiency of solar PV panels.

The hybrid system is expected to play a very important role now and in the future. The amount of heat energy that can be recovered is very important in determining the overall efficiency of this hybrid system. High efficiency indicates that hybrid systems have advantages over single solar PV systems [113]. Table 3 shows a summary of the literature review of the efficiency of PV/T systems using water and air as a PV panel cooling method.

Table 3. Summary of literature review of PV/T system efficiency.

Author	Study Location	Cooling Method	PV Efficiency	Thermal Efficiency
Mojumder et al. [114]	Bangladesh	Water	9.3%	30.0%
Ibrahim et al. [115]	Malaysia	Water	11.4%	55.0–62.0%
Kiran and Devadiga [116]	India	Water	8.2%	57.9%
Ahn et al. [117]	South Korea	Air	15.0%	23.0%
Li et al. [118]	China	Air	10.6%	50.0%
Good et al. [119]	Norway	Air	12.0%	71.5%
Alzaabi et al. [120]	UAE	Water	15.0–20.0%	60.0–70.0%
Palaskar and Deshmukh [121]	India	Water	12.4%	71.4%
Daghigh et al. [122]	Malaysia	Water	8.9%	90.0%
Jahromi et al. [123]	Iran	Water	9.7%	54.7%
Hazami et al. [124]	Tunisia	Air	15.0%	50.0%
Hu et al. [125]	China	Air	7.7%	28.0%
Rounis et al. [126]	Canada	Air	16.5%	48.0%
Mojumder et al. [127]	Malaysia	Air	13.8%	56.0%
Yazdanifard et al. [128]	Iran	Water	17.0%	70.0%
Al-Shamani et al. [129]	Malaysia	Water	13.5%	81.7%
Rosa-Clot et al. [130]	Italy	Water	13.2%	62.0%
Khanjari et al. [131]	Iran	Water	13.2%	55.0%
Su et al. [132]	China	Water and air	11.8%	64.4%
Othman et al. [133]	Malaysia	Water and air	17.0%	76.0%

7.2. Heat Pump

The heat pump acts as a mechanism for transporting heat from one place (heat source) at low temperature to another (heat sink) at high temperature. Currently, many new technologies are being applied with heat pumps for various use purposes. Integration between heat pumps and solar energy is one example application used to transfer heat generated through solar energy for the purpose of heat reuse for hot water use, space heating and more. Mohanraj et al. [134] studied the development of a solar assisted compression heat pump system (SACHP) to reduce conventional electricity consumption which could conserve the environment and reduce the problem of global warming. The study discusses in detail the system configuration, modeling, and system performance of any potential enhancements.

Heat pumps are widely used in conjunction with solar energy for daily use such as for heating, drying, and desiccation purposes. Daghigh et al. [135] and Fadhel et al. [136] conducted a study of heat pump applications for use in drying activities in Turkey. Whereas Ni et al. [137] and Chu and Cruickshank [138] conducted research on the application of heat pumps for the purpose of heating space in winter. Heat transfer and production for hot water use were studied by Hepbasli and Kalinci [139] and Buker and Riffat [140] in Turkey and the United Kingdom respectively. In addition, there was a study on desalination of seawater via heat pump by Kalogirou [141] in the country of Cyprus. However, there have been no studies on the application of heat pumps for the purpose of cooling the air-ventilated spaces in hospital wards especially in tropical climates such as this one.

Although heat pumps were identified as an efficient tool for generating large amounts of heat, electricity is still required for it to operate. However, the electricity required by the heat pump will be transmitted by the solar PV panel via a hybrid system. PV/T integrated heat pumps such as the SACHP concept can improve overall system efficiency. This hybrid system not only enhances the efficiency of the PV panel but also enhances the thermal efficiency of the heat collector and heat pump in providing optimum output in any application purpose. There were many studies on heat pumps as summarized by Mohanraj et al. [134] in Table 4. Based on these studies, heat pumps have the potential to integrate with various other sources of energy such as solar energy, gas engines, carbon dioxide, underground sources, wastewater, and advanced systems.

Table 4. Summary of previous heat pump study [134].

Author	Year	Country	Study Topic
Ozgener and Hepbasli [91]	2007	Turkey	Solar assisted heat pumps
Hepbasli et al. [142]	2009	Turkey	Gas engine drive heat pumps
Chua et al. [143]	2010	China	Advances in heat pump systems
Austin and Sumathy [144]	2011	Canada	Carbon dioxide heat pumps
Omojaro and Breitkopf [92]	2013	Germany	Direct expansion solar assisted heat pumps
Amin and Hawlader [93]	2013	Singapore	Solar assisted heat pumps in Singapore
Sarbu and Sebarchievici [145]	2014	Romania	Ground source heat pumps
Hepbasli et al. [146]	2014	Turkey	Waste-water heat pumps
Kamel et al. [94]	2015	Canada	Solar energy integration with heat pumps
Fischer and Madani [147]	2017	Germany	Heat pumps in smart grids

7.3. Hybrid PV/T and Heat Pump System

Generally, solar PV systems work to generate electricity through renewable energy as shown in Figure 3 to reduce dependence on grid systems and reduce carbon emissions to the environment. In addition to electricity, PV panels also produce unnecessary heat energy that can affect the efficiency of the system. Currently, various heat collector technologies are introduced to absorb heat from PV panels and transfer them to other areas acting as heat sinks. The basic concept of a PV/T hybrid system that combines solar PV and heat collector is as in Figure 4.

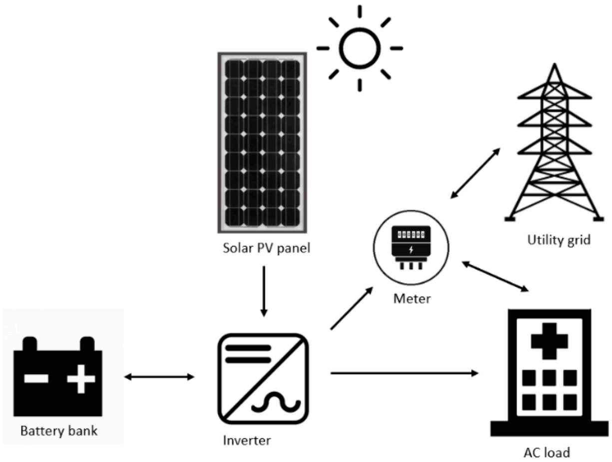

Figure 3. Solar PV system.

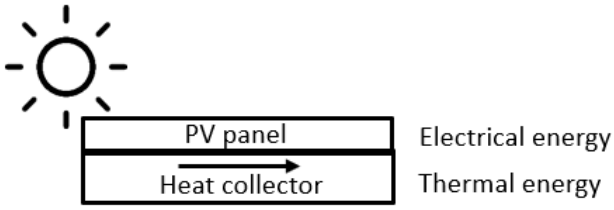

Figure 4. Basic concept of PV/T system.

The ability to generate electricity on its own as well as energy saving and heating space requirements is a key requirement for all buildings. This was also studied by Fischer and Madani [147] who saw the integration of solar PV and heat pumps as a very effective method to save more electricity. The ability of PV/T systems to absorb unnecessary heat to improve solar PV efficiency enables more electricity to be generated. At the same time, the heat collected by the heat collector can be reused for a variety of other purposes.

However, the introduction of heat pumps as a component to PV/T is seen as a great potential in providing a new system that is more energy efficient overall. This concept has been given particular attention by Hadorn [89] and Kamel et al. [94] in their writing and research as a field of study for any development and potential improvements to the hybrid system. The heat pump is able to provide flexibility to the power system if the correct design approach is implemented. The collected heat can be stored in storage tanks before reuse for heating or cooling purposes and the production of hot water via heat pumps. Operation of heat pumps during free electricity (solar PV usage) or at low rates (off-peak hours) gives the building owners the option to save energy and utility costs [90].

In this regard, the application hybrid solar PV and heat pump systems for the purpose of cooling space in natural ventilation wards is advisable because they are capable of providing optimum energy savings. The production of electricity through solar PV systems can also be used to operate heat pumps without affecting existing energy demand as well as offsetting energy usage through the grid. The reduction in energy demand from the grid during peak hours prevents consumers from being charged to the maximum demand by energy suppliers and also helps to maintain national energy reserves. The hybrid system is expected to improve thermal comfort in wards without air conditioning and provide comfortable environment for patients and hospital staff.

8. Discussion

The main research gap was identified as a result of the problem statement and literature review. Almost all government hospitals under the MOH provide naturally ventilated wards for patients needing treatment. In addition to the high cost of providing air-conditioned wards, the addition of daily operating costs was also a factor in the decision.

MOH has undertaken various strategies of energy saving and efficiency as well as the use of renewable energy to maintain financial capability in delivering services. Green building initiatives are seen as the solution to this problem. However, the green building rating not only focuses on energy efficiency but also emphasizes other aspects including IEQ which aims to ensure the comfort of the indoor environment to the occupants. Very few studies were conducted to improve thermal comfort in natural ventilated ward hospitals. Furthermore, according to the authors' literature review, no solution was provided through the energy cogeneration method at government hospitals which was found to optimize the energy consumption produced while solving thermal comfort problems in tropical climate-controlled natural ventilation. Most studies focus only on the use of heat energy for hot water and for the purpose of heating space in winter.

An appropriate new method or finding should be sought to provide thermal comfort in naturally ventilated wards while maintaining energy saving and energy efficiency in hospitals. According to Yau et al. [20], mechanical ventilation systems are very important in helping to improve the indoor environment. However, installing air conditioning in natural ventilated ward is not the best way to solve this problem as it contributes toward increasing energy consumption and daily operating costs. Fan use is the easiest retrofit method to improve thermal comfort based on a study by Lomas and Giridharan [87] in a hospital ward in the United Kingdom. However, the increase in the use of electric fans is also not likely to provide optimum thermal comfort with the weather and tropical climate of the country as well as the current state of hospital building cover that does not meet the best practices of passive design.

Specific research is needed in the wards to bridge the knowledge gap on thermal comfort [20]. For the purpose of improving thermal comfort, Lan et al. [71] developed a building model for natural ventilated ward in Singapore national hospitals and analyzed several passive solutions such as window type conversion and thermal chimney. The results showed a 32% increase in thermal comfort after a louvered window repair. However, thermal comfort calculations are based on data obtained through simulation rather than actual measurements or long-term monitoring in the field.

Passive roof technologies such as radiation barriers and cool paint were studied by Tong et al. [84] to look at thermal performance in residential buildings in Singapore while number of passive cooling and hybrid cooling strategies have been studied to improve thermal comfort in office buildings at Putrajaya using natural ventilation. According to Moosavi et al. [85], cross ventilation has a very high impact on improving thermal comfort in the atrium area while also enhancing the performance of other passive cooling strategies. The use of double facade façade also contributes to increased thermal comfort in tropical climate office buildings in Rio de Janeiro, Brazil. A study by Barbosa et al. [86] found that thermal comfort can be achieved by almost 70 percent of total building hours occupied by the application of double skin façade.

Various approaches were taken to improve thermal comfort for low-energy building occupants. Most of the research focuses on buildings in tropical climates but very little research has been done on hospital buildings especially for natural ventilated ward. From the literature study, the hybrid photovoltaic/thermal and heat pump system (HPVTHPS) shows a great potential to solve the thermal comfort problem at the hospital natural ventilated ward as shown in Figure 5.

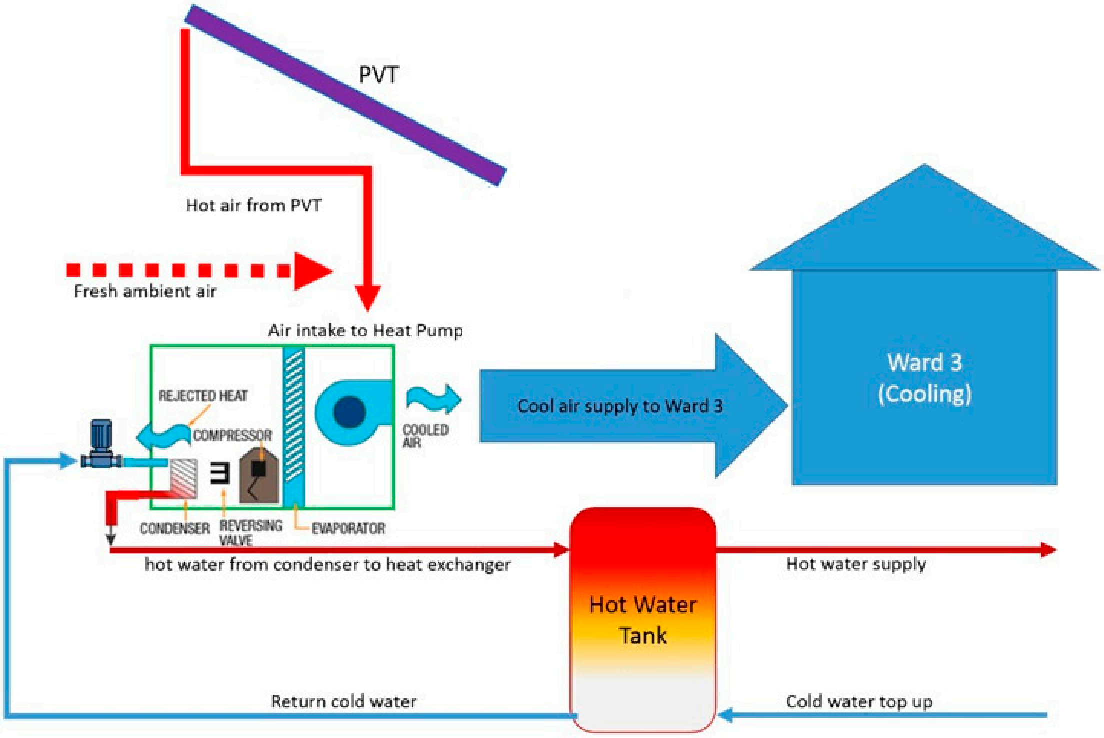

Figure 5. Proposed concept of hybrid PV/T and heat pump system for naturally ventilation ward.

In principle, the heat energy generated by the solar PV panels will be absorbed and recycled by the heat pump to be cooled by the proposed system. Since most hospital requires hot water in its daily operation, the hot air absorbed by heat pump will be channeled to hot water system. The resulting cold air will be channeled to natural ventilated ward to improve the thermal comfort of ward residents including hospital staff and patients. This method is seen as a new finding for thermal comfort solutions in natural ventilated ward tropical hospitals using energy cogeneration applications. It will not only have the potential to reduce cost of electricity through the use of solar power, but also improve the efficiency of solar PV panels as all the heat generated is absorbed by the proposed system. This fact is supported by a study conducted by Rahman et al. [148] in which the efficiency and production of electricity is reduced with each heat increase of 1 °C on the solar panel. In addition, this system also indirectly provides cooler roofs and will reduce solar heat gain in hospital buildings.

9. Conclusions

The results of this research are very important to assist the government in providing better services to patients by optimizing available resources. The use of new and environmentally friendly technologies is also in line with the government's goal of reducing carbon emissions and conserving the environment. There are several research gaps that have been identified as the starting point of the research to be undertaken. The literature review of natural ventilation wards and associated issues involving public hospitals including climate, energy management, and thermal comfort led to important information needed for further research to improve thermal comfort and energy saving in the area. Subsequently, a literature review of solar PV/T systems and heat pumps led to the suggestion of a hybrid system as a solution to the problem of thermal comfort in natural ventilation wards at tropical climate government hospitals with temperatures averaging throughout the year. Based on the previous experimental study of hybrid PV/T and heat pump system in the same climate condition, average efficiency of solar PV is 11.88% and maximum efficiency thermal generation per hour is 88.68% when solar irradiance varies from 300 to 1000 W/m^2. Average values of coefficient of performance (COP) of heat pump is 6.14 which indicates the high performance of the installed heat pump [149]. It shows that the hybrid PV/T and heat pump system could be a good solution to improve solar PV efficiency and produce hot water efficiently. However, the system could be further enhanced for the purpose of cooling the naturally ventilated ward space to improve thermal comfort inside the building.

This research is both novel and contributes significantly to the government as there is still no empirical study on the hybrid system on-site for the purpose of cooling the natural ventilation space especially involving health facilities such as public hospital wards in tropical climate conditions. It is also recommended that a case study be conducted in the hospital with such a hybrid system on-site to evaluate the thermal comfort improvement in the ward and overall energy performance as well as performance of the installed system.

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