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Preliminary Techno–Environment–Economic Evaluation of an Innovative Hybrid Renewable Energy Harvester System for Residential Application

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Abstract: A technical, environmental, and economic feasibility study for a patented hybrid renewable energy harvester system for residential application is conducted in this paper. This system can be mounted on top of an existing residential building to provide electricity from renewable sources. The system is characterized by its V-shaped roof guide vane (VRGV) that directs and augments airflow into the wind turbine, to enhance the rotational and power generation performance of the wind turbines in low wind speed areas. Furthermore, the VRGV increases the installation area for the solar photovoltaic panels and expand the rainwater collection area for the building, and facilitates natural ventilation and prevents excessive solar radiation into the room. The environment–economic evaluation of the system is conducted based on the life-cycle cost (LCC) in terms of low carbon and economic cost-effectiveness. The evaluation of the system with dimensions of 15 m (L) × 16 m (W) × 17.05 m (H) showed that the annual energy generated is 21.130 MWh. Annual low-carbon benefit of the system is estimated to be 11.894 t. The cumulative net present value (NPV) of the system in the life cycle time (20 years) is \$52,207.247, with the consideration of a discount rate of 8%; also, the cash flow breakeven occurs in the 11th year. It is important to note that the carbon payback period (CPP) of the system is five years.

Keywords: hybrid renewable energy; energy harvester system; V-shape roof guide vane; technical feasibility; low-carbon benefit; economic evaluation; life cycle cost

1. Introduction

The use of traditional fossil fuels is a main source of power generation and environmental pollution in the world. Increase in energy consumption is also a major issue faced by all countries in the world. According to the forecast by the International Energy Agency, global energy consumption is expected to increase by 53% in the year 2030 [1]. However, among this energy consumption, electricity has been

recognized as the main way of energy consumption in many countries, and it is also accepted as one of the driving forces of economic development around the globe [2]. The challenge of continuously generating electricity and meeting the growing energy demands is exerting tremendous pressure on the energy infrastructures for many developed and developing countries [3,4]. In the growing energy consumption industries, the residential building industry is considered to be the fastest growing power consumption industry, and it is expected to grow by a rate of 48% from 2012 to 2040 [5].

Malaysia mainly relies on thermal power generation, and its power resource comes from fossil fuel (natural gas, coal, and oil). Natural gas has been the major fuel for electricity generation in Malaysia since the early 1980s [6]. As of 2009, almost 94.5% of the electricity in Malaysia was generated from fossil fuel [7]. About 55.9% of the fuel for electricity generation in 2010 emanated from natural gas, followed by coal (36.5%), hydropower (5.8%), and oil (1.8%) [8]. According to the report of Malaysia energy commission, the total installed capacity in Malaysia, as of December 2016, was about 22,919 MW, of which the natural gas installed capacity accounted for 49%, and the coal installed capacity accounted for 40% [9]. Therefore, it can be seen that thermal power generation is one of the main sources of CO₂ emissions in Malaysia with the annual consumption of fossil fuel, which is about 1.6 billion tons [10], and the pollutant emission coefficient per kW h in Malaysia is higher than the world average level [11]. Thus, adopting renewable energy to generate power is an important technical method to reduce pollutant emissions. The use of wind and solar power generation as highly clean energy technologies produces almost no pollutants and has higher environmental value than the thermal power generation.

As the main alternative fuel for the power industry in the future, the environmental value of wind and solar power technologies cannot be ignored due to CO₂ emission reduction. Furthermore, large-scale wind farms and solar farms have been widely accepted around the world in recent years due to the diversification of market demands, thus also providing more development space for small-scale wind and solar farms [12]. There are a number of urban buildings in Malaysia. The wind energy resources of the building's roof and space are abundant. In addition, Malaysia is rich in solar energy resources and annual rainfall due to its proximity to the equator, which provides a good external environment for the design and application of the hybrid renewable energy harvester systems for residential buildings. This paper will conduct a techno-environment-economic evaluation for the hybrid renewable energy harvester system installed on a residential building based on Malaysia's climate data and carbon footprint data.

In this paper, the technical features of a patented hybrid renewable energy harvester system are reviewed. An environmental evaluation is done by adopting the low-carbon benefit methods and carbon footprint analysis, to estimate the environmental benefits of the system. Economic evaluation is performed by using the life-cycle cost (LCC) method to calculate the cost and benefit of the system in the entire life-cycle.

2. Existing Renewable Energy Utilization Systems

In these contemporary times, the renewable energy harvester has become a major research topic to address problems caused by environmental pollution, climate change, and increased fossil fuel consumption [13]. In comparison to a large hybrid wind-solar power system, small-scale wind and solar power systems have been extensively researched and applied in the industrial and residential industries [14,15]. Similar to all alternative energy sources, the initial investment costs of the solar and wind power systems are expensive, but cheaper in terms of the operating and maintenance costs. In addition, a hybrid system that is based on the combination of a solar photovoltaic (PV) and wind turbine technology can achieve a more stable annual power generation, where the solar PV and wind turbine can complement each other to achieve an efficient use of the hybrid system. For example, Zahnd et al. tested a small-scaled solar-wind hybrid model with lead-acid batteries in a Nepal village. The results from their experiment showed that the solar PV panels and wind turbine complemented each other to meet the load or storage in the lead-acid battery, and this hybrid system was able to

extend the average power generation time by 3 to 4 h per day [16]. Furthermore, Bekele and Palm studied the feasibility of integrating a wind–solar power system with a diesel generator for residential application in a remote area [17]. According to an economic analysis, this system took a shorter time to break even when compared with a single energy generation system. Therefore, a power generation system with an auxiliary and supplementary energy support is more competitive than a stand-alone power generation system. Jurasz et al. studied the effect of energy complementarity of a small-scale hybrid power system on the efficiency and reliability of a particular hybrid system [18]. The important technical task for a hybrid energy power system used in the building is to obtain the optimal size and configuration, so as to achieve a high efficiency and economy of the system [19]; for example, Ekren et al. developed a new method for optimizing the size of a hybrid wind–solar system integrated with the battery bank and analyzed the economics of the system [20]. Fathy developed a method to optimize the size of a hybrid system consisting of PV modules, wind turbines, and fuel module based on local solar radiation data, wind speed, and ambient temperature, with the aim of reducing the system annual load coverage cost [21]. In addition, Yang et al. went ahead to propose an innovative optimized technique for the hybrid wind–solar system, which has the ability to estimate the optimal configuration of the system and minimize the system cost [22].

Equipping a building with efficient renewable energy (solar, wind, and rainwater) is one of the effective ways to solve the issues of high energy consumption and pollution in modern cities. Previous researchers have indicated that about one-third of the global carbon dioxide emissions are related to residential and commercial buildings [23–25]. The application of the renewable energy concept in architectural design is attracting people's interest, as researcher such as Yang et al. conducted a research on applying solar energy, wind energy, and rainwater on a house to achieve a high economic and ecological value [26]. Consequently, Chong et al. proposed a hybrid wind–solar–rain utilization system with a power augmentation guide vane (PAGV) for high-rise building applications, where the PAGV guided and increased wind speed into the wind turbine to improve power performance of the wind turbine that was installed in this system. According to the calculations that were undertaken, the system produced or saved a total of 160 MWh of electricity per year [27,28]. Moreover, the PAGV was able to act as a mounting bracket for solar panels and also acted as a rainwater harvester to reduce the electricity consumption of the high-rise building. In addition, building roof is considered to have a great potential for adopting renewable energy (wind, solar, and rain). Contino et al. investigated the possibility of a large-scale use of wind turbines combined with roof solar panels in rural and remote areas [29].

3. Economic and Environment Evaluation of Solar and Wind Power Generation

There are many economic–environmental performance indicators used in the field of product evaluation, such as LCC [27,30–32], LCA (life-cycle assessment) [33–35], LCOE (levelized cost of energy) [36,37], NPV (net present value) [31], EPBT (energy payback time) [38], ROI (return on investment) [39], BCR (benefit-to-cost ratio) [40], IRR (internal rate of return) [39], UEC (unit energy cost), and PBP (payback period) [31,39,41].

Lenzen [42] studied and summarized the wind power technology based on the LCC theory, in which the manufacturing materials, production techniques, and material recycling rates were taken into account. Other scholars, including Krauter et al., also evaluated the ability of photovoltaic power generation to reduce greenhouse gases, considering the stage of production, transportation, and installation of each component of a photovoltaic system, and the stage of operation and recycling of the photovoltaic power station [43]. More so, Korsavi et al. calculated the annual energy production, economic performance, and carbon dioxide emissions of 14 rooftop photovoltaic systems with a power of 5 kW by using the methods of PBP, NPV, ROI, and LCOE [44]. Wang et al. evaluated the performance of a small-scale horizontal axis wind turbine in terms of greenhouse gas emissions, energy consumption, electricity production, and economic benefits by using the LCA method [34]. Two cases of Oman's hybrid solar–wind power system were investigated and compared by LCC and other

methods. The results showed that the energy cost of the hybrid system located in Masira and Halaniyar were 0.182 \$/kW h and 0.222 \$/kW h, respectively [45]. Nookuea et al. studied the relationship between the LCC and the reliability of a hybrid solar–wind system with battery in the shrimp cultivation industry in Thailand [46]. The research on the LCC of the renewable energy power generation system (wind turbine and solar PV panels) involves all stages from the raw material processing to the end of life, however its main concentration is on the manufacturing stage [35,47,48].

Low-carbon benefit evaluation is based on the characteristics of the carbon emission reduction from photovoltaic and wind power generation, which is the algebraic sum of low-carbon positive and negative benefits that are generated during the whole life cycle. The low-carbon income of photovoltaic or wind power represents the economic benefits of the low-carbon benefits through the carbon trading mechanism. Kannan et al. [49] studied the potential low-carbon benefits and low-carbon income of a 2.7 kWp photovoltaic system. In their study, the construction, operation, and recovery phases of the photovoltaic power plant were considered. Furthermore, Ito et al. [50] analyzed six different large-scale solar photovoltaic systems using the LCA method and calculated the carbon dioxide emission intensity and the energy recovery period of the system. The result showed that the photovoltaic system with thin-film battery has the shortest carbon and energy recovery period.

4. Design Description of the System

This patented hybrid renewable energy harvester system consists of an energy generation system and an energy recovery system, where wind and solar energy are applied to generate electricity for the energy demands of a residential building where the system is installed. In addition, a rainwater harvester, heat rejection air vent, and natural daylight harvesting system, are applied to save part of the water and electricity for the residents. The design of this hybrid renewable energy harvester system is developed based on Malaysia's climate experience data. This system can be blended into a building structure with minimal negative visual impact, as shown in Figure 1. The demonstration model of the system is shown in Figure 2.



Figure 1. Artistic expression of a hybrid renewable energy harvester system for a residential building.



Figure 2. The model of the system.

The overview of the hybrid renewable energy harvester system is illustrated in Figure 3. The parameters of this system are listed in Table 1.

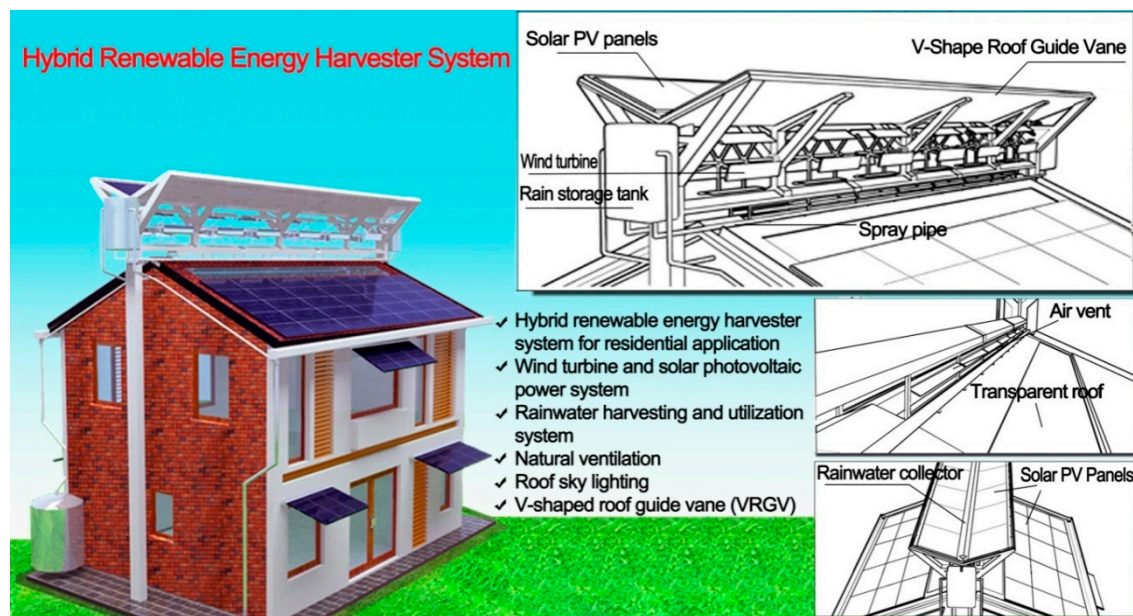


Figure 3. Overall structure layout.

Table 1. Specific parameters of the hybrid renewable energy harvester system.

Item	Value
Length of the main body of the building	15.0 m
Width of the main body of the building	16.0 m
Elevation of the main body of the building	13.05 m
Inclination angle of double-sloped roof	15.0° [51]
Length of the VRGV	15.0 m
Width of the VRGV	5.0 m (both sides)
Elevation of the VRGV	17.05 m
Tilt angle of the VRGV	19.5° [52]
Length of skylight window	12.0 m
Width of skylight window	1.0 m
Height space for the wind turbines installation	1.6 m
Location of the system	300°–320° (North-northwest)

The most visible feature of the system is a V-shaped roof guide vane (VRGV), installed on top of the building, which helps in concentrating the airflow from a large area and increasing the wind speed into the wind turbine. The VRGV and the double slope roof acts as a concentrator and diffusor to reduce the cross-section of the wind flow by the venturi effect to make the wind turbines generate more energy in the low wind speed areas. The VRGV is inclined at an angle of 19.5 degrees from the horizontal axis, which is known to be an optimized inclined angle for the wind concentration effect [52]. The VRGV can overcome the inferior aspect of the low wind speed by guiding and increasing the speed of the wind by 63% at the location of the wind turbines [52].

4.1. Energy Generation System

Six vertical axis wind turbines (VAWTs) are placed on the roof ridge for the generation of electricity. The parameters of the VAWTs are shown in Table 2. The rotational and power performance of the VAWTs installed in this hybrid renewable energy harvester was optimized by the increased wind speed caused by the VRGV [30].

Table 2. Specific parameters of the wind turbine [53].

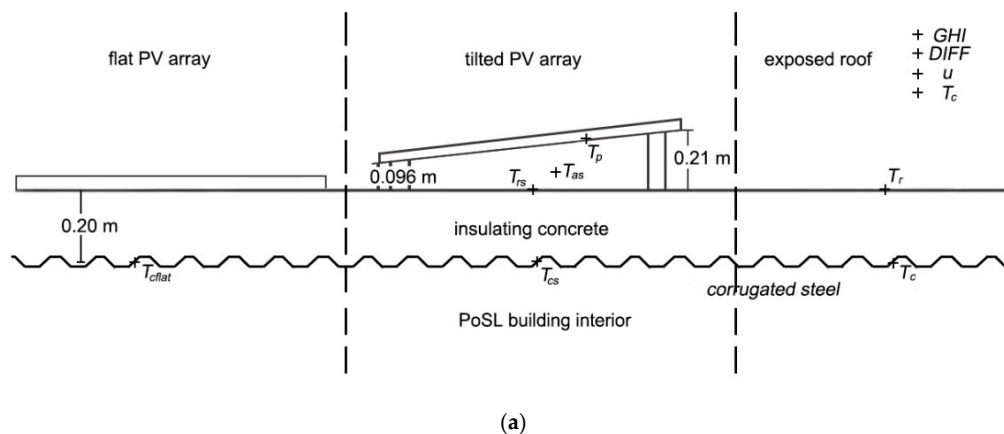
Items	Dimensions
Rated power	300 W
Output voltage	24 V
Operation wind velocity	1.8–25.0 ms^{-1}
Starting-up wind velocity	1.8 ms^{-1}
Rated wind velocity	12 ms^{-1}
Shutdown wind velocity	35 ms^{-1}
Coverage area of a wind turbine (length \times diameter), A	1.4 m \times 1.2 m
Blades	5
Product life	20 years

Solar panels can be strategically placed on top of the pitched roof and the VRGV, as shown in Figure 3. Solar panels are not placed on the part of the pitched roof where noon sunlight is blocked by the VRGV. The specifications of the solar PV panel are shown in Table 3.

Table 3. Parameters of the solar photovoltaic (PV) system.

Parameters	Values
Rated power [54]	300 W
Maximum voltage [54]	36 V
Maximum current [54]	8.33 A
Module size	
Size of module [54]	1956 \times 992 \times 50 mm
Area of a solar PV panel	1.94 m^2
Percentage of active area of a solar PV panel [55]	75%
Active area of a solar PV panel, A_{cells}	1.455 m^2
Total number of the solar PV panels	112 (84 on double-sloped roof and 28 on V-shape roof)
Total effective areas of the solar PV panels, A_s	157.14 m^2
Life cycle	20 years

According to Dominguez et al.'s research on the effect of roof-mounted solar PV panels on the ceiling temperature [56], Figure 4 shows the temperature measured in the experiment for the cases of roof tilted PV array, roof flat PV array, and exposed roof. From the result, it was discovered that the negative heat effect on a roof with tilted and flat PV arrays is less than that of an exposed roof. Therefore, the roof-mounted tilted solar PV panels in this hybrid renewable energy harvester system were more conducive to keeping an indoor comfortable temperature.

**Figure 4.** Cont.

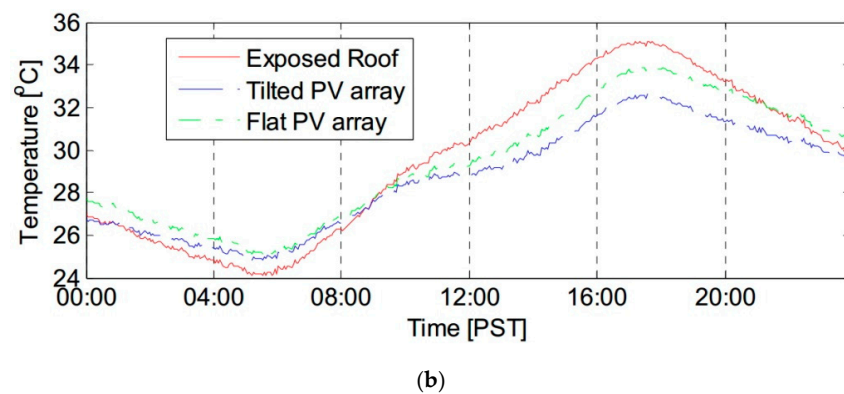


Figure 4. (a) Schematic diagram; (b) interior ceiling surface temperatures under exposed roof, tilted PV array, and flat PV array. Reprint with permission from Reference [56]; 2011, Elsevier.

4.2. Energy Recovery System

A rainwater harvester comprises two water tanks, drainage channels, water spray pipes, connecting pipes, etc. In this system, the VRGV also forms the flow path for the rainwater collection that leads towards the water storage tanks, as shown in Figure 5. In the current study, a simplified passive automatic cleaning and cooling system with a water spray function was used to increase the power generation efficiency of the solar PV modules (refer to Figure 6). Sixteen equally spaced copper nozzles are applied in this cleaning and cooling system to maintain a uniform cleaning and cooling effect of the solar PV modules. According to the experiments conducted by Elnozahy et al. [57], the power generation efficiency (11.7%) of the cooled and cleaned solar PV modules was 2.7% higher than that of the solar PV modules without the cooling and cleaning system. Figure 7 shows the efficiency of the PV module with and without the cooling system.

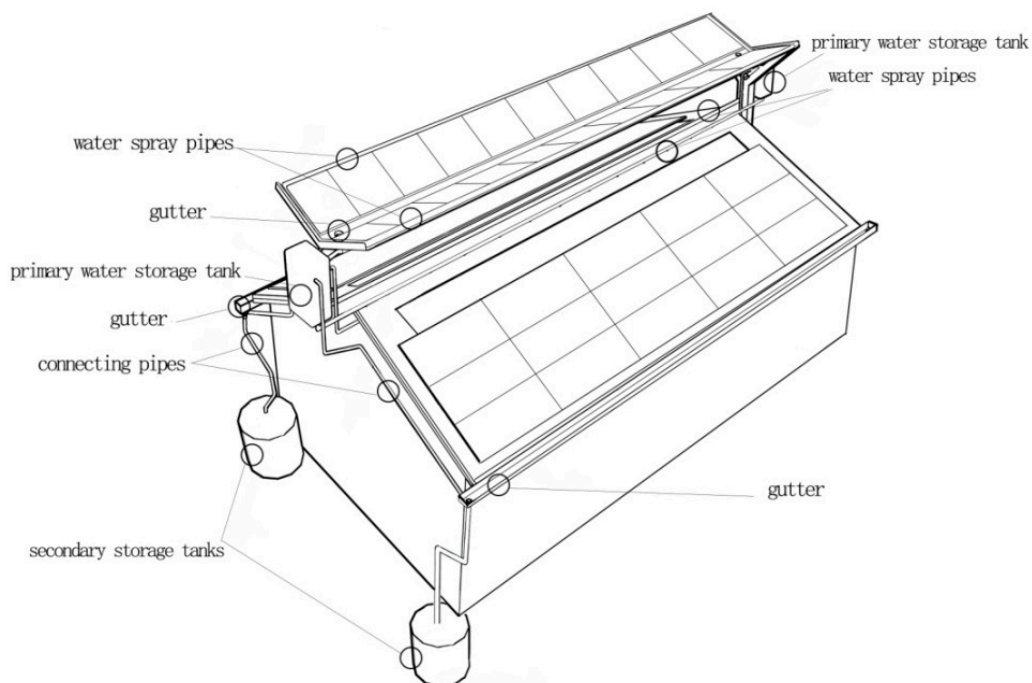


Figure 5. Rainwater harvester.

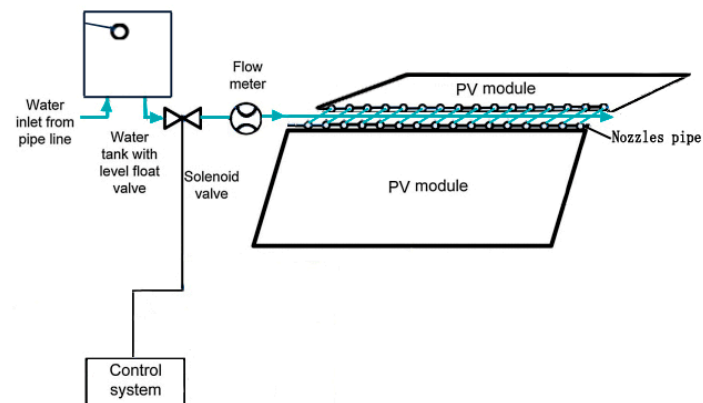


Figure 6. Automatic cooling and cleaning system.

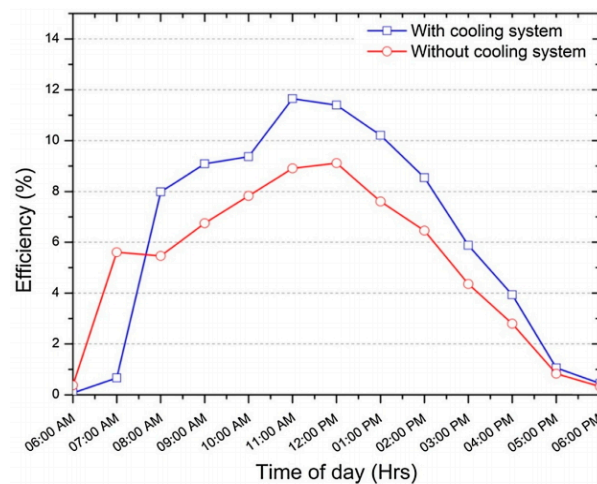


Figure 7. Photovoltaic efficiencies of the PV modules with and without the cooling system. Reprint with permission from Reference [57]; 2015, Elsevier.

The hybrid renewable energy harvester system is also incorporated with a daylight harvesting system. Skylight windows are located on the double-sloped roof, which is close to the roof ridge and under the upper the VRGV; hence, the VRGV is able to prevent direct sunlight into the room at noon, as shown in Figure 8. Two skylight windows located at the center of the double-sloped roof of the building can be used to illuminate the space where daylight is difficult to access from the window. The skylight windows of this hybrid renewable energy harvester system can save a total energy of approximately 1.840 MWh per year and can replace about 18 lamps (each of 35 W) [58].

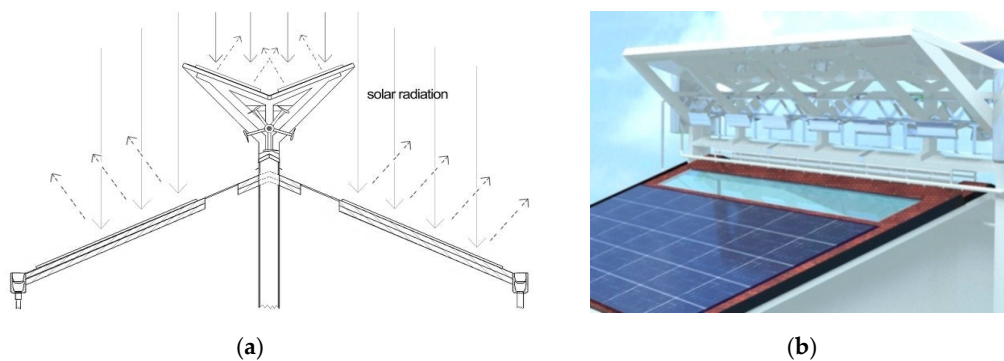


Figure 8. Daylight harvesting system diagrams: (a) Schematic diagram; (b) skylight windows.

Along the ridge of the building, a heat rejection air vent is adopted to exhaust warm air from the building, as shown in Figure 9. When wind flow blows through the area between the VRGV and the double-pitched roof, the wind can be accelerated, creating a low-pressure area, while the warm air in the attic possesses a higher pressure. Natural convection occurs due to the pressure difference between the attic and the area where the VAWT is located. A simple computational fluid dynamics (CFD) analysis was implemented to research on the pressure distribution between the VRGV and the double-pitched roof. The result showed that the night ventilation cooling effect of a windowed building equipped with this hybrid renewable energy harvester system (air vent) was $2.9\text{ }^{\circ}\text{C}$, assuming an average outdoor temperature of $30\text{ }^{\circ}\text{C}$ and an outdoor temperature fluctuation of $5\text{ }^{\circ}\text{C}$ [58]. Additionally, rainwater is prevented from entering the building by a series of side louvers along the air vent.

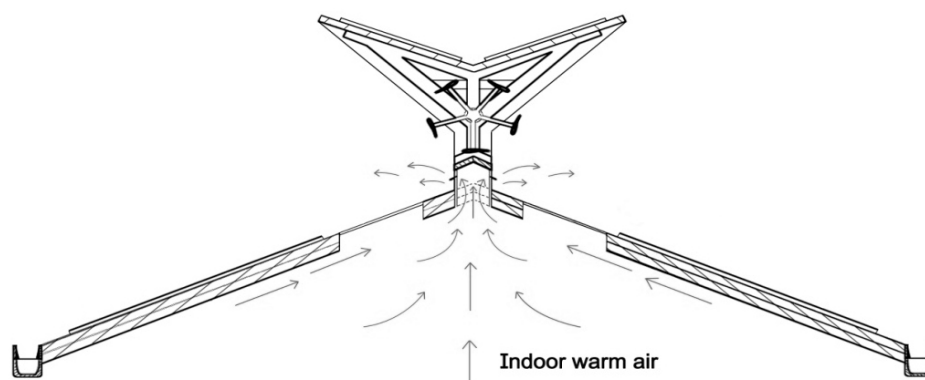


Figure 9. Schematic diagram of ventilation.

5. Methodology: Environment and Economic Evaluation

Solar PV power generation and wind power generation are characterized by low carbon, environmentally friendliness, and sustainability. This study conducted the environmental evaluation and economic evaluation for all aspects of the hybrid renewable energy harvester system installed on a building, including the component production, transportation, installation, operating, and maintenance, as shown in Figure 10. The LCC method was applied in this study, which took into account the cost of each stage and the fluctuation of the operating and maintenance cost, tariff rate, discount rates, and tax rate. The task of the LCC assessment method is the evaluation of the costs, process, and structure of the product by identifying the energy, materials used, and wastes released to the environment.

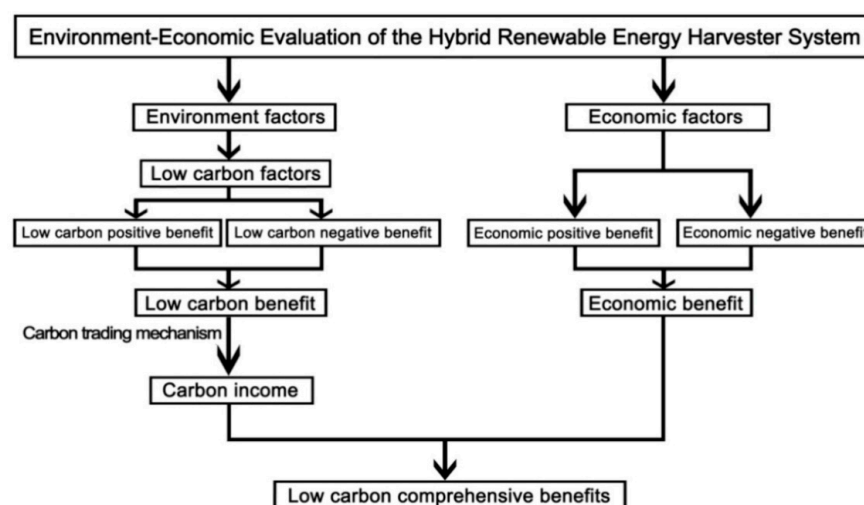


Figure 10. Framework of low-carbon comprehensive benefit.

In the present study, only the environmental and economic evaluation of the solar energy system and the wind energy system of the hybrid renewable energy harvester system were analyzed. The environmental and economic evaluation of the rainwater harvester and the heat rejection air vent in this hybrid renewable energy harvester system were not considered. The environmental and economic evaluation of the system was conducted based on its technical characteristics and the meteorological data obtained from Subang city, Malaysia. (Lat.: 3°4'25" N and Long.: 101°35'17" E), as shown in Figure 11. To conduct the environmental and economic evaluation for the system, the climate, economic, and financing characteristics of Malaysia were used. In this study, it is assumed that the electricity generated by the proposed hybrid energy system is fed into the urban electricity network.



Figure 11. Map of Subang city, Malaysia.

Solar and wind power generation can reduce traditional fuels consumption and carbon emission; furthermore, solar and wind power generation also has some economic benefits. Therefore, the revenue link of the solar and wind power generation is a positive factor of the low-carbon economy. The cost link of the solar and wind power generation is a negative factor of the low-carbon economy. This paper conducts a low-carbon and economic analysis for all aspects of the solar photovoltaic power generation over a life cycle.

5.1. Output of the System

5.1.1. Output of the Solar Energy System

The climatic condition in Malaysia is favorable for the development of solar energy due to the abundant sunshine throughout the year. In this study, the solar radiation data used in the calculations were collected at a weather station in Subang. The power output of the solar photovoltaic panel can be estimated by the following equation:

$$G_{solar} = G_s \cdot A_s \cdot K \cdot \epsilon_{pv} \cdot \eta_{ps} \cdot PR \quad (1)$$

where, G_s is the annual average solar radiation value (kW h m^{-2}); A_s is the effective area of the solar PV panels (m^2); K is the shadow influence factor; ϵ_{pv} is the influence factor of the dip angle and orientation of the solar module on the energy output; η_{ps} is energy conversion efficiency of the solar module; and PR is the system performance ratio. The average monthly solar radiation in Subang, Malaysia is shown in Figure 12. The calculation parameters are shown in Table 4.

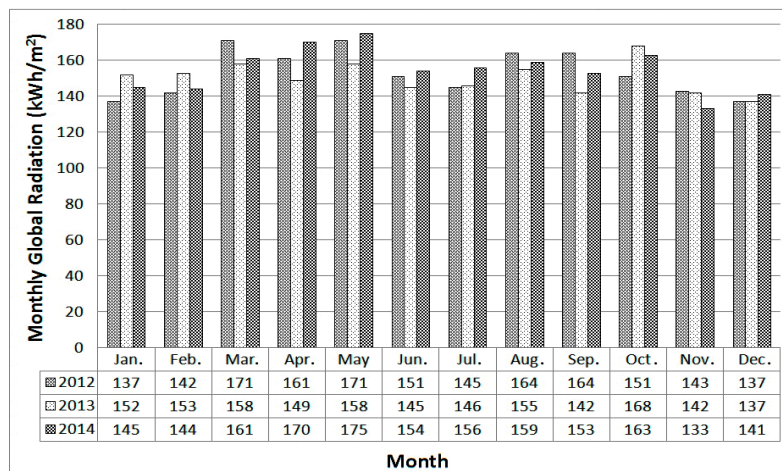


Figure 12. Monthly average solar radiation (kW h/m²) data of Subang, Malaysia (2012–2014).

Table 4. Parameters for solar PV panel calculation.

Parameters	Values
Shadow influence factor, K [58]	69.4%
Influence factor of dip angle and direction of solar PV panel, ε_{pv} [55]	0.95
Module conversion efficiency, η_{ps} [55]	15%
System performance ratio, PR [55,59]	71.8%

5.1.2. Output of the Wind Energy System

Six VAWTs are applied on the building roof, as shown in Figure 13. The wind turbines are installed in a space between a double-sloped roof and the VRGV, where the wind flow into the wind turbines can be augmented. Hence, the wind energy can be converted into electricity through these wind turbines. The electricity generation from the wind turbines can be calculated using Betz law of wind power:

$$G_{wind} = \frac{1}{2} \rho \cdot C_p \cdot \eta_g \cdot \eta_{WD} \cdot A \cdot (V')^3 \quad (2)$$

where ρ is the air density; C_p is the rotor efficiency; η_g is the wind turbine efficiency; η_{WD} is the loss factor in the wind direction; A is the coverage area of the blades of a wind turbine; V' is the increased wind velocity at the region of the wind turbine from the ground in the presence of the optimized VRGV structure. In this case, six VAWTs with a rated power of 300 W (Diameter = 1.2 m) were selected to match the building, and they were readily available and cheap in the market; also, the dimension matched the selected building.

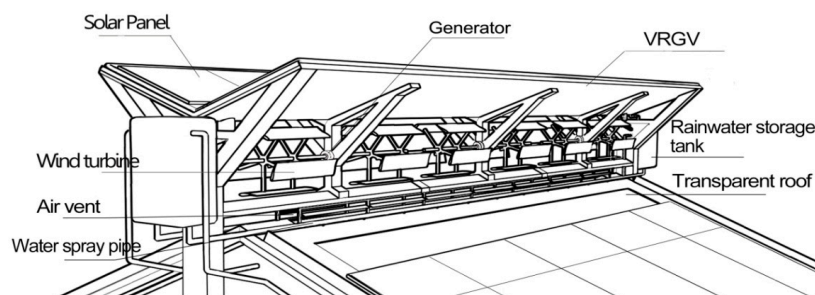


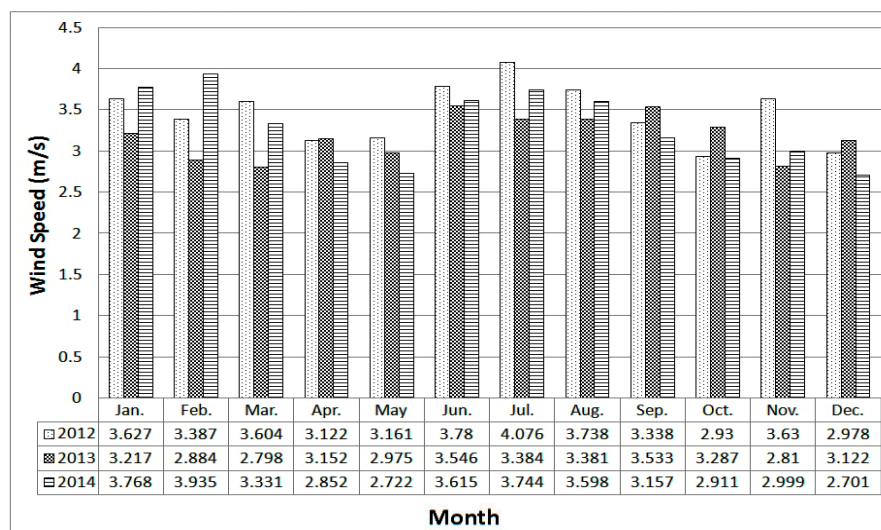
Figure 13. Wind energy system of the hybrid renewable energy harvester system.

Table 5 shows the parameters for calculating the electricity generation from the wind energy system.

Table 5. Parameters for calculating the electricity generation of the wind turbine [58].

Elements	Dimensions
Air density, ρ	1.225 kg/m ³
Rotor efficiency, C_p	0.4
Wind turbine efficiency, η_g	0.8
Loss factor in wind direction, η_{WD}	0.9
Coverage area of the blades, A	1.4 m \times 1.2 m

According to the studies (including CFD simulations and experimental tests), the shape of the VRGV was optimized for the maximum utilization of wind energy, and the optimized wind velocity increased by a factor of 1.63 due to the optimized VRGV design being found. Therefore, the increased wind velocity (V') data in the presence of the optimized VRGV at the region of the wind turbine (height of 11.1 m) in Subang, Malaysia are listed in Figure 14.

**Figure 14.** The increased wind velocity in the presence of the optimized V-shaped roof guide vane (VRGV) structure at the region of the wind turbine in Subang (m/s) (2012–2014).

5.2. Low-Carbon Benefit of the System

In this article, low-carbon benefit is the algebraic sum of carbon emission reductions (low-carbon positive benefit) and carbon emissions (low-carbon negative benefit) from the solar and wind power generation of the system during the life cycle. The annual low-carbon benefit of the system is expressed as

$$C_n = C_1 - C'_2 \quad (3)$$

where C_1 refers to the annual carbon dioxide emission reduction of the solar and wind power generation; C'_2 ($C'_2 = C_2/n$) refers to the annual carbon dioxide emission of the solar and wind power generation, that is, the annual carbon cost generated by the system; C_2 is the carbon cost of the system, mainly referring to the initial carbon investment cost and maintenance carbon cost; whereas n is the life of the solar and wind energy system.

Annual carbon dioxide emission reduction (low-carbon positive benefit) of the solar and wind power generation is calculated as follows:

$$C_1 = (G_{solar} + G_{wind})m_c \quad (4)$$

where m_c is the local (Malaysia) carbon dioxide emission factor for power generation (kg/kW h).

The carbon cost (low-carbon negative benefit) of the solar and wind energy system is calculated as follows:

$$C_2 = C_{0s} + C_{0w} + C_{ms} + C_{mw} \quad (5)$$

where C_{0s} is the initial carbon investment cost of the solar energy system; C_{0w} is the initial carbon investment cost of the wind energy system; C_{ms} is the maintenance carbon cost of the solar energy system; and C_{mw} is the maintenance carbon cost of the wind energy system. Furthermore, the initial carbon investment cost mainly considers the carbon dioxide emission generated during the process of the raw material production, equipment manufacturing, equipment transportation, and construction of the solar PV panels and wind turbines.

5.2.1. The Carbon Cost of the Solar Energy System

The initial carbon investment cost of the solar energy system (C_{0s}) is expressed as

$$C_{0s} = kP_0m_c + W_1gS_1 + \sum_{i=1}^m \lambda_i G_i \quad (6)$$

where k is the electric energy consumed by the producing unit power solar photovoltaic panel (kW h/kW); P_0 is the total capacity of the solar energy system (kW); W_1 represents the total weight of the solar energy system (kg); g is the carbon dioxide emission intensity of the transportation (kg/t·km); S_1 is the distance between the location of the solar PV panel manufacturer and the project site (km); m is the species of material required to install the solar PV panels; i is the i th material required to install the solar PV panels; λ_i is the carbon dioxide emission coefficient of the i th material (kg/kg); and G_i is the weight of the i th material (kg).

The maintenance carbon cost of the solar energy system (C_{ms}), mainly considering the carbon dioxide emission from the operation and routine maintenance of the solar PV panels as well as the components replacement of the solar PV panels, is expressed as follows:

$$C_{ms} = C_{0s} \cdot \beta \quad (7)$$

where β is the ratio of the carbon cost of the operating and maintenance versus its initial carbon investment.

Furthermore, the parameters used in the process of estimating the carbon cost of the solar PV power generation of the hybrid renewable energy harvester system installed on a residential building are listed in Table 6.

5.2.2. The Carbon Cost of the Wind Energy System

In this study, a crane was used throughout the process of the construction of the wind turbines. Also, the carbon dioxide emission of the working crane was considered as the major part of the carbon footprint in the process of the wind turbines construction. The initial carbon investment cost (C_{0w}) of the wind energy system is calculated as follows:

$$C_{0w} = \sum_{j=1}^n G_j \lambda_j + W_2 g S_2 + W_3 g S_3 + m_{crane} h \quad (8)$$

where n represents the species of materials required for the wind turbine fabrication; j is the j th material required for the wind turbine fabrication; G_j is the weight of the j th material (kg); λ_j is the carbon dioxide emission coefficient of the j th material (kg/kg); W_2 is the total weight of the wind power system (kg); g is the carbon dioxide emission intensity of the transportation (kg/t·km); S_2 is the distance between the location of the wind turbine manufacturer and the project site (km); W_3 is the weight of the crane (t); S_3 is the distance between the location of the crane and the project site (km); m_{crane} is the

mass of the carbon dioxide emission per hour by the working crane (kgCO_2/hr); while h denotes the working hours of the crane (hr).

Table 6. Specific parameters for evaluating the carbon cost of the solar energy system.

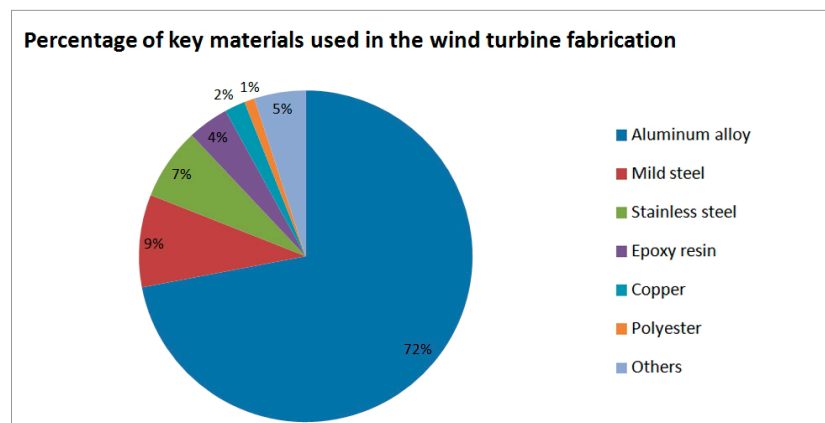
Item	Unit	Value
Local carbon dioxide emission factor for power generation (Malaysia), m_c	kg/kW h	0.726 [60]
Electric energy consumed by producing unit power solar photovoltaic panel, k	kW h/kW	2525 [61]
Total capacity of the solar energy system, P_0	kW	33.6
Total weight of the solar energy system, W_1	kg	2968 (26.5 kg/PV panel \times 112) [62]
Carbon dioxide emission intensity of the transportation, g	Kg/t·km	0.12 [63]
Distance between the solar PV panel manufacturer location and the project site, S_1	km	339 *
Weight of the i th material, G_i * (*Assuming that only the industrial aluminum profile bracket structure is used for the installation of the solar PV panels, and an inclined roof solar panel structure is adopted for installation)	kg	876.28 ** [64]
Carbon dioxide emission coefficient of the i th material (industrial aluminum profile), λ_i	kg/kg	2.148 *** [65]
Ratio of operating and maintenance carbon cost of the solar energy system versus its initial carbon investment, β		5% [66,67]
Life of the solar PV system, n	year	20

*. The distance between Penang (solar panel manufacturer location) and Subang (project location); **. In present study, the installation area of the solar PV system is 217.32 m^2 ($1.956 \text{ m} \times 0.992 \text{ m} \times 84 + 1.956 \text{ m} \times 0.992 \text{ m} \times 28 = 217.32 \text{ m}^2$), the amount of industrial aluminum profile used for installation is 4.0322 kg/m^2 ; ***. Carbon dioxide emission coefficient of industrial aluminum profile during production process.

Consequently, $\sum_{j=1}^n G_j \lambda_j$ is the carbon dioxide emission in the process of the wind turbine fabrication. The main components and required materials in the wind turbine fabrication are shown in Table 7 [68,69]. The percentage of the key materials used in the wind turbine fabrication is shown in Figure 15.

Table 7. Main components and key manufacturing materials of the wind turbine.

Component	Item	Main Manufacturing Materials
Rotors	Blade	Aluminum alloy
	Hub	Aluminum alloy
Nacelle	Generator cover	Mild steel, copper, lubricant, silica
		Aluminum alloy, epoxy resin
Supporting Structure	Main shaft bracket	Stainless steel
		Mild steel
Others	Transformer	Mild steel, copper, lubricant, silica
	Gearbox	Carbon steel, iron

**Figure 15.** Percentage of key materials used in the wind turbine fabrication. Reprint with permission from Reference [68]; 2006, SAGE.

Moreover, the quality of the key materials that are required for the wind turbine fabrication and the corresponding carbon dioxide emission coefficient is shown in Table 8 [70–74]. The carbon dioxide emission coefficient is determined by summing up the environmental impacts of the corresponding material at each stage of the life cycle [75,76].

Table 8. Quality of the key materials required for a wind turbine fabrication and the corresponding carbon dioxide emission coefficient.

Material	Aluminum Alloy	Mild Steel	Stainless Steel	Epoxy Resin	Copper	Polyester	Others (Carbon Fiber, etc.)
Quality, G_j (t)	$0.04 \times 72\%$	$0.04 \times 9\%$	$0.04 \times 7\%$	$0.04 \times 4\%$	$0.04 \times 2\%$	$0.04 \times 1\%$	$0.04 \times 5\%$
Carbon dioxide emission coefficient, λ_j (t CO ₂ eq/t)	14.4	2.3	4.7	4.4	5.1	3.94	3.07

Additionally, W_{2gS_2} is the carbon dioxide emission in the transportation of the wind turbines. The transportation carrier of the wind turbine is a vehicle. The vehicle consumes fuel and produces carbon dioxide emissions during the transportation of the wind turbines. The parameters for estimating the carbon dioxide emission in the wind turbines transportation are listed in Table 9.

Table 9. Parameters for estimating the carbon dioxide emission in the wind turbines transportation.

Item	Unit	Value
Total weight of the wind energy system, W_2	t	0.18 (6 wind turbines)
Carbon emission intensity during the transportation, g	kg/t·km	0.12 [63]
Distance between the wind turbine manufacturer location and wind power plant, S_2	km	8.2 *

* The distance between Puchong (wind turbine manufacturer location) and Subang (project location).

In this study, the carbon dioxide emission of the crane is considered to be the main carbon consumption required for the installation process of the wind turbines. The carbon dioxide emission generated in the transporting of the crane (W_3gS_3) should be taken into consideration. In this study, it is assumed that a lorry, using diesel, transports the crane to the project site. Additionally, the carbon dioxide emission in the process of the working crane ($m_{crane}h$) should be considered. Therefore, the parameters for estimating the carbon dioxide emission during the installation process of the wind turbines are shown in Table 10.

Table 10. Parameters of estimating the carbon dioxide emission in the crane transportation.

Item	Unit	Value
Weight of the crane, W_3	t	3.9 *
Carbon dioxide emission intensity of the transportation, g	Kg/t·km	0.12 [63]
Distance between the location of the crane and the project site, S_3	km	8.2 **
Mass of carbon dioxide emission per hour by the working crane, m_{crane}	Kg CO ₂ e/hr	5 [77]
Working hour of the crane, h	hr	1

*. Weight of MAEDA mini crawler crane (MC-305C-2); **. The distance between Puchong (crane location) and Subang (project location).

The maintenance carbon cost of the wind energy system (C_{mw}) mainly considers the carbon dioxide emission generated in the operational process and the routine maintenance of the wind turbines as well as the components replacement of the wind turbines, and it is expressed as follows:

$$C_{mw} = C_{0w} \cdot \beta' \quad (9)$$

where β' is the ratio of the operating and maintenance carbon cost of the wind energy system versus its initial carbon investment of 5% [78].

5.3. Economic Benefit of the System

The annual economic benefit of the system can be estimated by the following equation:

$$E_n = E_1 - E'_2 \quad (10)$$

where E_1 refers to the annual economic income of the solar and wind energy system; E'_2 ($E'_2 = E_2/n$) refers to the annual economic cost of the solar and wind energy system; E_2 refers to the economic cost of the solar and wind energy system; and n indicates the life of the system.

The annual economic income of the solar and wind energy system (economic positive benefit) can be calculated by the following equation:

$$E_1 = (G_{solar} + G_{wind}) P_r \quad (11)$$

where P_r refers to the feed-in tariff (FiT) rates of the renewable energy generation.

The economic cost of the solar and wind energy system (E_2) mainly includes the initial investment, operating, and maintenance cost as well as the equipment replacement cost. The operating and maintenance cost coupled with the equipment replacement cost need to take the price inflation rate into consideration. Hence, the economic cost of the solar and wind energy system is calculated by following Equation (12). Also, the details of the initial capital cost, operating and maintenance cost, and the equipment replacement cost are shown in Table 11. The economic cost of the system is calculated as follows:

$$E_2 = \sum_{t=1}^{t=n} [(I_t + E_{opt})(1+i)^{-t}] \quad (12)$$

where I_t is the capital investment in the t th year; E_{opt} is the operating and maintenance cost and the equipment replacement cost in the t th year; and i is the inflation rate.

Table 11. Detailed cost of the system.

Item	Value (USD)
Solar PV panels [58]	\$27,000.00
Wind turbines [58]	\$3600.00
VRGV [58]	\$5000.00
Grid-Connected inverter * [79]	\$4400.00
Grid-tie controller (including dump load) * [80]	\$2300.00
Installation cost [58]	\$2000.00
Estimated initial capital cost **	\$44,300.00
Operating and maintenance cost per kW h of solar energy system [81]	\$0.011
Operating and maintenance cost per kW h of wind energy system [82,83]	\$0.029

*. Inverter and controller are replaced every ten years; **. The value includes transportation cost.

5.4. Annual Comprehensive Benefit of the System

Based on Equations (3) and (10), the annual comprehensive benefit of the system (E) can be obtained as follows:

$$E = P_T C_n + E_n \quad (13)$$

where P_T is the carbon trading price; $P_T C_n$ is the annual low-carbon economic benefit of the system.

The economic reference data for assessing the annual comprehensive benefit of the system are described in Table 12.

Table 12. Economic reference data for assessing the annual comprehensive benefit of the system.

Item	Unit	Value
FiT rates of renewable energy generation, P_r	USD/kW h	0.20 [84]
Carbon trading price, P_T	USD/kg	0.012 [85,86]

5.5. Carbon Payback Period (CPP) of the System

CPP is the ratio of the initial carbon investment cost of the solar and wind energy system to the annual low-carbon benefit from the system. It is given as:

$$CPP = \frac{C_{0s} + C_{0w}}{C_n + C_m} = \frac{C_{0s} + C_{0w}}{C_1 - C'_2 + C_3 - C'_4} \quad (14)$$

6. Results and Discussion

6.1. Electricity Generation by the Hybrid Renewable Energy Harvester System

According to Equation (1), the specifications of the solar PV panel in Table 3, the monthly solar radiation of Subang city, Malaysia in Figure 12, and other calculation parameters in Table 4, the annual electricity generation by the solar energy system is calculated to be approximately 20.433 MWh/year. With reference to Equation (2), the specifications of the wind turbine in Table 2, the parameters for calculating the power output of the wind turbine in Table 5, and the wind speed data at the region of the wind turbine in Figure 14, the annual electricity generation by the wind energy system is approximately 0.697 MWh/year. The building with the hybrid renewable energy harvester system is placed to face the north-northwest in the fourth quadrant (300°–320°) in order to take advantage of as much wind energy as possible, as shown in Figure 16.

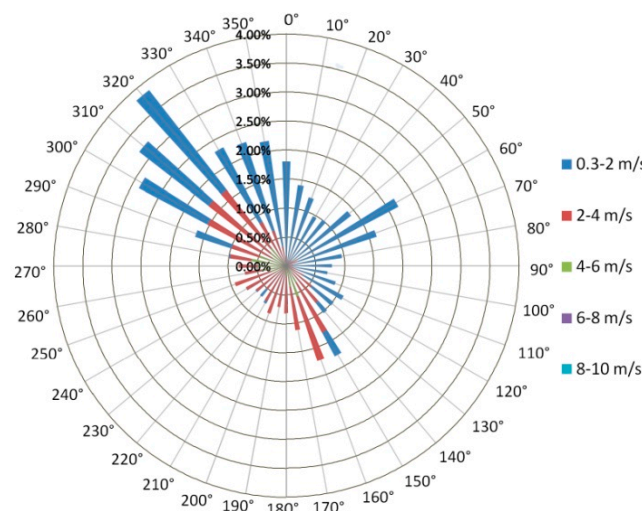


Figure 16. Wind direction frequency in Subang.

6.2. Low-Carbon Benefit of the Hybrid Renewable Energy Harvester System

Solar and wind power generation can reduce the consumption of traditional fuels, thus helping to reduce carbon emissions. Therefore, the carbon dioxide emission reduction of this hybrid renewable energy harvester system is considered as a low-carbon positive factor. The initial carbon investment cost of the system (including the process of raw material production, equipment manufacturing, equipment transportation, and system installation) and the maintenance carbon cost of the system are the low-carbon negative factors. In this study, it is assumed that the life cycle of the system is 20 years. According to Equation (4) and the result from Section 6.1, the annual carbon dioxide emission reduction of the system is estimated to be 15.340 t. According to Equations (6) and (8) and the parameters in Tables 8–10, the initial carbon investment cost of the system is estimated to be 65.653 t. With regards to Equations (7) and (9), the maintenance carbon cost of the system is calculated to be 3.283 t. Thus, the annual low-carbon benefit of the system is estimated to be 11.894 t based on Equation (3). According to Equation (14), the CPP of the hybrid renewable energy harvester system is calculated to be about five years.

6.3. Economic Evaluation of the Hybrid Renewable Energy Harvester System

The LCC approach was adopted to estimate the investment costs and economic benefits throughout the life cycle; moreover, it calculates the payback period of the capital and operating costs as well as the NPV over the life cycle. In the economic evaluation of the system, some economic parameters need to be considered, including the FiT rate, fluctuation rate of the FiT, extra property tax, market discount rate, operating and maintenance price, fluctuation rate of the operating and maintenance price, the fluctuation rate of the extra property tax, etc. Furthermore, the commodity price (including energy price) fluctuation in Malaysia is mainly determined by market factors, while the government regulatory measures also have an impact on the energy price [87]. The commercial FiT rate of renewable energy generation is about \$0.2/kW h [84], as shown in Table 12. According to the trend of the FiT rate in Malaysia, its rate is assessed to be 10% per year [27]. The additional property tax and the market discount rate are expected to be 2% and 8%, respectively [27,88]. Furthermore, the operating and maintenance price of the solar and wind energy system is expected to be \$0.011 per kW h [81] and \$0.029 per kW h [82,83], increasing by 2.13% per year according to the price trends [89]. Detailed economic parameters for the economic evaluation are listed in Table 13.

Table 13. Economic parameters.

Category	Item	Value
Cost	Inflation rate of inverter price	2.13%
	Inflation rate of controller price	2.13%
	Inflation rate for operating and maintenance cost	2.13%
	Inflation rate of extra property tax	2.13%
	Additional property tax	2%
Profit	Inflation rate of feed-in tariff [24]	10%
	Market discount factor [88]	8%

The saving (E) of this hybrid renewable energy harvester system is the difference of the commercial electricity tariff rate ($CETR$) and the cost of energy production (CEP) which is given as

$$E = CETR - CEP. \quad (15)$$

However, the present worth factor (PWF) is employed to define the economic revenue of this hybrid renewable energy harvester system. In this study, it is assumed that the annual electricity output of the system is replicated and the feed-in tariff fluctuates at a rate of i yearly, hence the PWF is estimated by the following formula:

$$PWF(N, i, d) = \sum_{j=1}^N (1+i)^{j-1} / (1+d)^j. \quad (16)$$

where N is the period for the economic estimation, i is the fluctuation rate, and d is the market discount factor. In order to determine the present value (PVE) of the income for the N th year, the following equation is adopted:

$$PVE = 1 / (1+d)^N. \quad (17)$$

Thus, the NPV of the system is the summation of the present value within a given period of time and it is obtained from the aforesaid calculations. The economic evaluation of the hybrid renewable energy harvester system indicates that the cash flow breakeven appeared at the year of 11 (total 20-year life cycle). The cumulative NPV of the system over a cycle time (20 years) is \$52,207.25 under the condition of a market discount rate of 8%, as referred to in Figure 17. In the economic evaluation of the system, the initial carbon investment cost price, maintenance carbon cost price of the system, as well as the low-carbon economic profit price of the electricity generated by the system are taken into account;

those prices are calculated based on the international carbon trading price [85,86]. Table 14 shows the financial analysis of the system.

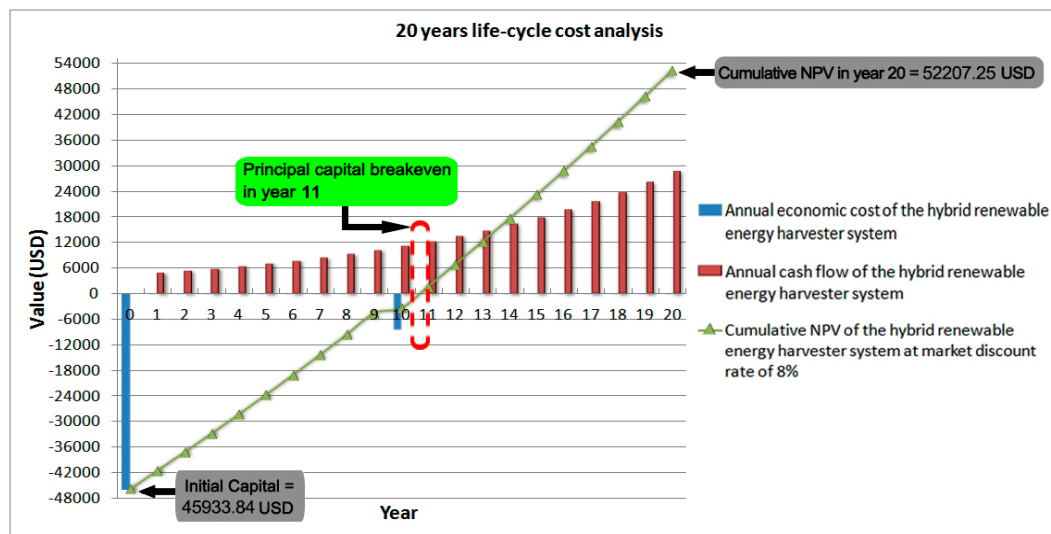


Figure 17. Cost-effectiveness analysis of the hybrid renewable energy harvester system in 20-year life cycle.

Table 14. The financial analysis of the hybrid renewable energy harvester system (solar and wind energy system) in Subang city, Malaysia (20-year life cycle).

Year	Capital Cost (\$)	Operating and Maintenance Cost (\$)	Inverter and Controller Replacement (\$)	Income (\$)	Annual Cash Flow (\$)	Discounted Cash Flow (\$)	Cumulative NPV (\$)
0	-45,933.840				-45,933.840	-45,933.840	-45,933.840
1		-252.172		4832.672	4580.500	4241.203	-41,692.637
2		-257.501		5297.531	5040.030	4321.013	-37,371.623
3		-262.944		5808.877	5545.933	4402.540	-32,969.083
4		-268.503		6371.357	6102.854	4485.780	-28,483.303
5		-274.180		6990.085	6715.905	4570.732	-23,912.571
6		-279.978		7670.686	7390.708	4657.400	-19,255.171
7		-285.900		8419.347	8133.447	4745.788	-14,509.383
8		-291.947		9242.874	8950.927	4835.907	-9673.476
9		-298.124		10,148.754	9850.630	4927.767	-4745.709
10		-304.432	-8271.954	11,145.221	2568.835	1189.868	-3555.841
11		-310.874		12,241.336	11,930.462	5116.770	1560.930
12		-317.454		13,447.062	13,129.608	5213.948	6774.877
13		-324.174		14,773.360	14,449.187	5312.936	12,087.813
14		-331.037		16,232.289	15,901.252	5413.757	17,501.570
15		-338.046		17,837.110	17,499.064	5516.435	23,018.005
16		-345.204		19,602.413	19,257.209	5620.996	28,639.001
17		-352.515		21,544.247	21,191.732	5727.467	34,366.468
18		-359.982		23,680.264	23,320.283	5835.878	40,202.346
19		-367.607		26,029.883	25,662.276	5946.259	46,148.605
20		-375.396		28,614.464	28,239.068	6058.641	52,207.247
					Net Present Value	52,207.247	

6.4. Sensitivity Analysis

Sensitivity analysis is conducted to investigate the impact of the variation of the input parameters on the low-carbon and economic benefits of the system and to determine the most sensitive parameters. In this study, the parameters varied in the sensitivity analysis includes solar radiation, wind speed, as well as some economic parameters (inflation rate of price). The model employed for this sensitivity analysis works as intended, which can ensure that the expected increase and decrease can be found.

6.4.1. Sensitivity Analysis of Solar Radiation

The solar radiation per month is varied from $133.119 \text{ kW h m}^{-2}$ (minimum) to $174.656 \text{ kW h m}^{-2}$ (maximum) between 2012 to 2014. In order to ensure consistency of the analysis, the wind speed,

solar PV panels, wind turbines, and the economic parameters have remained the same. As shown in Table 15, the power output of the system increases from 18.522 MWh/year to 24.083 MWh/year with an increase of 30.03% due to the increasing solar radiation values. Compared with the results calculated by the mean solar radiation value in this study, they decrease by 14.08% and increase by 13.98%, respectively. It is also observed that the annual carbon dioxide emission reduction of this hybrid renewable energy harvester system varies from 13.447 t to 17.484 t. The annual low-carbon benefit of the system increases from 10.000 t to 14.037 t, which reduces by 18.94% and increases by 18.01% comparing to the result in this study. Subsequently, the accumulated NPV of the system over a 20-year life cycle increases from \$39,598.765 to \$66,482.230, which decreases by 31.84% and increases by 27.34% compared to the accumulated NPV calculated in Section 6.3.

Table 15. The impact of solar radiation on the environmental and economic profitability variables in this system.

Input Parameters (Solar Radiation) (kW h m ⁻²)	Annual Power Output (MWh)	Annual Carbon Dioxide Emission Reduction (t)	Annual Low Carbon Benefit (t)	Accumulated NPV (20 Years) (USD)
133.119	18.522	13.447	10.000	39,598.765
174.656	24.083	17.484	14.037	66,482.230

6.4.2. Sensitivity Analysis of Wind Speed

Between 2012 and 2014, the monthly minimum and maximum wind speed at the location of wind turbines was 2.700 m/s and 4.075 m/s. In order to ensure consistency of the analysis, solar radiation, solar PV panels, wind turbines, and the economic parameters have remained the same. According to calculations, the power output of the system increases from 20.739 MWh/year to 21.487 MWh/year, as shown in Table 16. Compared with the energy generation of the system in this study, they decreased by 1.883% and increased by 1.69%, respectively. Additionally, it is observed that the annual carbon dioxide emission reduction of the system varies from 15.057 t to 15.600 t. The annual low-carbon benefit of the system increases from 11.610 t to 12.153 t. Subsequently, the accumulated NPV of the system over a 20-year life cycle increases from \$50,401.809 to \$53,795.838, which decreases by 3.58% and increases by 3.04% compared to the accumulated NPV calculated in Section 6.3.

Table 16. The impact of wind speed on the environmental and economic profitability variables in this system.

Input Parameters (Wind Speed) (m/s)	Annual Power Output (MWh)	Annual Carbon Dioxide Emission Reduction (t)	Annual Low Carbon Benefit (t)	Accumulated NPV (20 Years) (USD)
2.700	20.739	15.057	11.610	50,401.809
4.075	21.487	15.600	12.153	53,795.838

6.4.3. Sensitivity Analysis of Economic Parameter

According to the trend of cost price inflation rate in Malaysia in the past five years, the minimum and maximum price inflation rate of 0.98% and 3.79% are adopted to forecast the variations in the environmental and economic performance of the system. In order to ensure consistency of the analysis, solar radiation, wind speed, solar PV panels, and wind turbines have remained the same. Therefore, the power output, annual carbon dioxide emission reduction, and annual low-carbon benefit of the system are consistent with the results calculated in Sections 6.1–6.3. The accumulated NPV of the system over 20 years varies from \$52,880.810 to \$51,092.459, which increases by 1.29% and decreases by 2.18% compared to the accumulated NPV calculated in Section 6.3, as shown in Table 17.

In summary, solar radiation is the parameter with the largest impact on the variables related to the environmental and economic profitability (power output, carbon dioxide emission reduction, low-carbon benefit, and accumulated NPV) of the hybrid renewable energy harvester system at the selected installation location (Subang, Malaysia).

Table 17. The impact of cost price inflation rate on the environmental and economic profitability variables in this system.

Input Parameters (Cost Price Inflation Rate)	Annual Power Output (MWh)	Annual Carbon Dioxide Emission Reduction (t)	Annual Low Carbon Benefit (t)	Accumulated NPV (20 Years) (USD)
0.98%	21.130	15.340	11.894	52,880.810
3.79%	21.130	15.340	11.894	51,092.459

7. Conclusions

In this paper, a techno–environment–economic analysis has been conducted on a novel hybrid renewable energy harvester system for a residential application with an electricity generation system (VAWTs and solar PV system) and a recovery system (rainwater utilization system, heat rejection air vent, and daylight harvester). This system can partially meet the energy requirements of the building where it is installed and help to make the electricity supply of the building partially independent. The most visible feature of the system is a VRGV, which is installed on top of the building; it augments the wind flow to reach the wind turbines to improve the power performance of the wind turbines. This technical viability study shows that a wind velocity percentage increment of 63% can be obtained in the presence of the VRGV with an inclination angle of 19.5° via CFD simulations and experiments. The VRGV design can enhance the self-starting behavior of the VAWT mounted on the double-sloped roof by 13.78% more than that of the case without the VRGV [30]. Higher power coefficient values can be achieved by the VAWT mounted in this hybrid renewable energy harvester system with the VRGV, than that of the case without the VRGV. Taking into account the characteristics of the VRGV and its impacts on the building, the preliminary results show the possibility of its application in the areas with low wind speed.

Furthermore, the energy generation analysis shows that a residential building with the hybrid renewable energy harvester system in Subang city, Malaysia (length 15 m \times width 16 m \times height 17.05 m) including six VAWTs (length 1.4 m \times diameter 1.2 m) and 112 solar photovoltaic panels (length 1.956 m \times width 0.992 m) can generate 21.130 MWh/year.

The carbon emission reduction analysis shows that the annual carbon dioxide emission reduction of the system is estimated to be 15.340 t, and the annual low-carbon benefit of the system is calculated to be 11.894 t over the life cycle, only considering the solar and wind energy systems in the assessment process. Also, the CPP of this system is estimated to be about five years.

Consequently, an economic evaluation of this hybrid renewable energy harvester system (only considering solar and wind energy system) has been carried out. In the economic evaluation, the initial carbon investment cost price and the maintenance carbon cost price of the solar power system and the wind power system, as well as the low-carbon economic profits of the electricity generated by the solar and wind system are taken into account. The result shows that the accumulated NPV of the hybrid renewable energy harvester system over a 20-year life cycle is \$52,207.25, under the condition of the market discount rate of 8%, and it was also indicated that a cash flow breakeven appeared at the 11th year.

This hybrid renewable energy harvester system can be retrofitted into a standardized configuration to be installed on an existing building for energy generation and saving, which can alleviate some problems of a hybrid energy system such as energy efficiency, visual impact, safety, and sensitivity to the wind. In this study, the selected location for the evaluation is located in a low wind speed area, hence the payback period of the system can be expected to be shorter in a high wind speed region.

For future study, a wind tunnel test will be conducted to study the detailed impact of the different wind directions on the power performance of the wind turbine in this hybrid renewable energy harvester system. Additionally, a field test will also be performed to investigate actual power generation and economic profits of an actual size prototype. In this study, only the environmental impacts and economic profits of the solar and wind energy system of the hybrid energy system were considered, without considering rainwater harvester, natural ventilation system, and daylight harvesting system. Therefore, a more comprehensive analysis methodology will be developed for this hybrid energy system in the future study.

8. Patent

A patent entitled “Wind harvester installation on a building” (Application NO: PI 2016703622) resulted from the project described in this paper (refer to Figure 18).

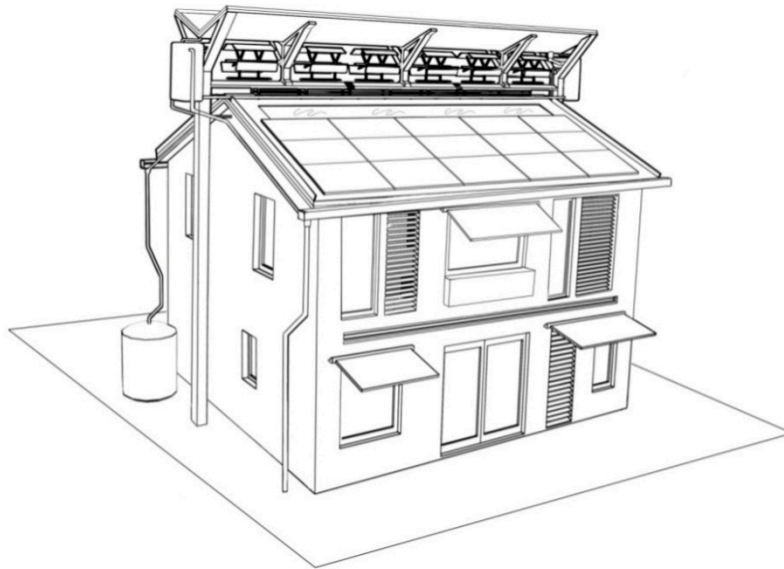


Figure 18. Harvester installation on a building.

Author Contributions: Conceptualization, X.W. and W.C.; methodology, X.W. and K.W.; software, X.W. and K.W.; data curation, L.S.; writing—original draft preparation, X.W.; writing—review and editing, X.X. and C.-T.W.; supervision, W.C. and S.L.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

VRGV	V-shaped roof guide vane
LCC	Life cycle cost
NPV	Net present value
CPP	Carbon payback period
PV	Photovoltaic
PAGV	Power augmentation guide vane
LCA	Life cycle assessment
LCOE	Levelized cost of energy
EPBT	Energy payback time
ROI	Return on investment
BCR	Benefit to cost ratio
IRR	Internal rate of return
UEC	Unit energy cost
PBP	Payback period
VAWTs	Vertical axis wind turbines
CFD	Computational fluid dynamics
PR	Performance ratio

CETR	Commercial electricity tariff rate
CEP	Cost of energy production
PWF	Present worth factor
PVE	Present value
A	Coverage area of a wind turbine
K	Shadow influence factor
N	Period for the economic estimation
A_{cells}	Active area of a solar photovoltaic panel
A_s	Total effective areas of the solar PV panels
G_s	Annual average solar radiation value
ε_{pv}	Influence factor of dip angle and direction of solar PV panel
η_{ps}	Module conversion efficiency
ρ	Air density
C_p	Rotor efficiency
η_g	Wind turbine efficiency
η_{WD}	Loss factor in wind direction
V'	Increased wind velocity
C_n	Annual low carbon benefit
C_1	Annual carbon dioxide emission reduction
C'_2	Annual carbon dioxide emission
m_c	Carbon dioxide emission factor for power generation
C_{0s}	Initial carbon investment cost of the solar energy system
C_{0w}	Initial carbon investment cost of the wind energy system
C_{ms}	Maintenance carbon cost of the solar energy system
C_{mw}	Maintenance carbon cost of the wind energy system
k	Electric energy consumed by the producing unit power solar photovoltaic panel
P_0	Total capacity of the solar energy system
W_1	Total weight of the solar energy system
g	Carbon dioxide emission intensity of the transportation
S_1	Distance between the location of the solar PV panel manufacturer and the project site
m	Species of material required to install the solar PV panels
i	i th material required to install the solar PV panels
λ_i	Carbon dioxide emission coefficient of the i th material
G_i	Weight of the i th material
β	Ratio of operating and maintenance carbon cost of the solar energy system versus its initial carbon investment
n	Life of the solar PV system
W_2	Total weight of the wind energy system
S_2	Distance between the wind turbine manufacturer location and wind power plant
W_3	Weight of the crane
S_3	Distance between the location of the crane and the project site
m_{crane}	Mass of carbon dioxide emission per hour by the working crane
h	Working hour of the crane
E_n	Annual economic benefit
E_1	Annual economic income
E'_2	Annual economic cost
I_t	Capital investment in the t th year
E_{opt}	Operating and maintenance cost and the equipment replacement cost in the t th year
P_r	FiT rates of renewable energy generation
P_T	Carbon trading price
d	Market discount factor

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