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Techno-economic analysis of a wind–solar hybrid renewable energy system with rainwater collection feature for urban high-rise application ☆

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ABSTRACT

The technical and economic feasibility study of an innovative wind–solar hybrid renewable energy generation system with rainwater collection feature for electrical energy generation is presented in this paper. The power generated would supply part of the energy requirements of the high-rise building where the system is installed. The system integrates and optimizes several green technologies; including urban wind turbine, solar cell module and rain water collector. The design was conceptualized based on the experiences acquired during the development and testing of a suitable wind turbine for Malaysian applications. It is compact and can be built on top of high-rise buildings in order to provide on-site renewable power to the building. It overcomes the inferior aspect on the low wind speed by channeling and increasing the speed of the high altitude free-stream wind through the power-augmentation-guide-vane (PAGV) before it enters the wind turbine at the center portion. The shape or appearance of the PAGV that surrounds the wind turbine can be blended into the building architecture without negative visual impact (becomes part of the building). The design improves the starting behavior of wind turbines. It is also safer to people around and reduces noise pollution. The techno-economic analysis is carried out by applying the life cycle cost (*LCC*) method. The *LCC* method takes into consideration the complete range of costs and makes cash flows time-equivalent. The evaluations show that for a system with the PAGV (30 m diameter and 14 m high) and an H-rotor vertical axis wind turbine (17 m diameter and 9 m high) mounted on the top of a 220 m high building, the estimated annual energy savings is 195.2 MW h/year.

1. Introduction

Alternative energy resources such as wind energy and solar energy have made public and private sectors interested to invest in energy generation from these sources extensively. The common drawbacks to wind and solar energy options are their unforeseeable nature and they rely on the climate changes. However, there are daily and seasonal complementary relationships between wind energy and solar energy. In addition, stable power output could be expected through the hybrid power system [1]. So, the problems can be partially overcome by integrating two or more resources in a proper combination to form a hybrid system, using the strengths of one source to overcome the weaknesses of the other [2]. For certain locations, the hybrid solar–wind power generation systems with storage banks offer a highly reliable source of power, which is suitable for electrical loads that need higher reliability [3]. In order to combine and optimize these energies, various technical and economic methods could be applied to achieve a trustable hybrid renewable energy system.

Presently, electricity is produced in rural power plants and transferred to urban areas. However, in many cases in developing countries, grid extension is impractical because of dispersed population, rugged terrain or both. Thus, on-site renewable energy systems represent an important role for narrowing the electricity gap in rural parts of the developing world, where progress in grid extension remains slower than population growth [4]. The concept of on-site renewable energy generation is to extract energy from renewable sources close to the populated area where the energy is required. The proposed wind–solar hybrid renewable energy system in this paper is a new and feasible design. It is compact and can be built on the top of high-rise buildings in order to provide on-site green power to that building or be fed into the national electricity grid line [5].

In this paper, the techno-economic characteristics of the patented wind–solar hybrid energy system are reviewed. Economic analysis is done by using the life-cycle costing (*LCC*) method to calculate the entire life-cycle cost such as the net present value and payback period of both capital and operating expenses over the life of the system. A complete *LCC* analysis takes into consideration the discount rates, interest rates, operation and maintenance costs,

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Nomenclature

A_c	rain catchment area
A_s	array active area (solar panel)
c	scale parameter
C_p	coefficient of power (wind rotor)
C_r	runoff coefficient
CTR	commercial tariff rate
CUE	cost of unit of energy
d	discount rate
E_{solar}	energy generated by solar system
ETR	effective tax rate
G_s	annual mean global irradiation
$h(V)$	Weibull probability distribution function
HAWT	horizontal-axis wind turbine
I	rainfall intensity
i	inflation rate
IP	interest payment
ITS	income tax savings
k	shape parameter
K	solar power loss
LCC	life cycle cost
N	period of economic analysis
NPV	net present value
P	power
PAGV	power-augmentation-guide-vane
P_{rmc}	power of wind (rmc)
PT	property tax
PV	photovoltaic
PV	present value
PWF	present worth factor
V	wind velocity
V_{rain}	rain water volume
VAWT	vertical axis wind turbine
WSRS	wind–solar–rain savings
z	height (above ground level)

Greek letters

α	wind friction coefficient
η_{ps}	PV module conversion efficiency
η_{tr}	bearing and transmission efficiency
η_g	generator efficiency
η_{PAGV}	PAGV efficiency
ρ	density

present value of money, etc. Challenges in using *LCC* include poor data availability, erratic economic changes, uncertainties regarding discount rate, asset life, and estimating future operating and maintenance costs [6]. This clean energy generation will definitely help to reduce the greenhouse gas emissions that causing significant impacts on global climate change. The intangible costs related to the environmental impacts including greenhouse gas emissions are omitted in this paper, although it is very important.

2. Existing wind energy and solar energy systems configurations

Besides wind–solar hybrid energy systems, other alternative resources are combined for a hybrid system with various configurations, such as solar–diesel, wind–diesel, wind–solar–diesel and solar–diesel–hydro-fuel cell [7–10]. A lot of research works have been done on the performance of photovoltaic (PV) and wind energy systems.

Compared to large scale wind turbines, small scale wind energy systems have been studied extensively as a part of hybrid systems for application in residential areas [11,12]. It is concluded that for a satisfactory benefit of a small scale wind system, the mean wind speed of the site needs to be close to the rated wind speed of power generation [13]. Besides technical feasibility of the small scale wind energy systems, financial and non-financial attributes of the systems are evaluated [14,15]. Up to this moment, the large size wind turbine application in urban areas has not been studied extensively.

Like all the alternative energy sources, wind and solar energies are expensive in terms of initial capital cost, but relatively inexpensive in terms of operating costs [16]. The main technical work in a standalone wind–solar system is to obtain an optimum size and configuration for the system and a supplementary energy source to achieve the efficient and economical utilization in the hybrid system [17]. Bekele and Palm [18] investigated the possibility of supplying electricity from a hybrid wind–solar system with a supplementary diesel generator to a remotely located place detached from the main electricity grid in Ethiopia. Size optimization of PV/wind hybrid energy conversion system with battery storage under various load conditions in Turkey was performed by simulations [19,20]. A new methodology in size optimization of an autonomous hybrid wind–solar energy system integrated with battery bank is developed and economic conditions of some cases are analyzed [21,22]. In addition, an economic comparison is made between two cases which are a standalone wind–solar hybrid energy system and a grid connected electricity supply. It is concluded that if the hybrid energy system is installed at a distance more than 4817 m, it is more economical than laying cable from the electricity grid. Yang et al. [2] and Diaf et al. [23] studied on optimal design of wind–solar hybrid systems with the employment of battery banks. Most of the studies analyzed their proposed configurations in various meteorological conditions. Moreover, it is suggested to reduce the cost and risk of hybrid renewable energy system by incorporating a third energy source (auxiliary source such as electricity grid) instead of increasing the hardware size [24].

Bakos and Tsagas [25] presented a feasibility study on a grid connected solar energy system technically and economically. Based on the methodology used; the technical characteristics of the systems were defined. Then, based on the meteorological data of solar radiation, extractable energy was calculated. Finally, the cost and payback period of energy generation of the system for different financial scenarios were calculated and compared with the conventional electricity grid price. It was concluded that for all economic situations, the expensive initial capital and long payback period of the solar system are an exorbitant factor for the implementation of a project in commercial scale. Except for some isolated areas (e.g. islands) where the cost of energy generation or electrical grid connection is high, the central grid-connected consumers would reluctant to purchase a solar system for their energy demands [26]. In a further research, Bakos and Tsagas [27] worked on a wind–solar hybrid system and used a similar methodology to evaluate it. The developed system is in parallel with the national electricity grid and was used to supply the electricity to a typical dwelling place. Based on the economic analysis, it was found that the period of time to make the system with positive turnover is less than for a single solar system. Therefore, the use of auxiliary energy source made the system more competitive in comparison with the stand-alone system. However, some governmental subsidies help to reduce the negative cash flow and payback periods to encourage private investors to move towards larger investments on renewable energy systems. From the reviews on current

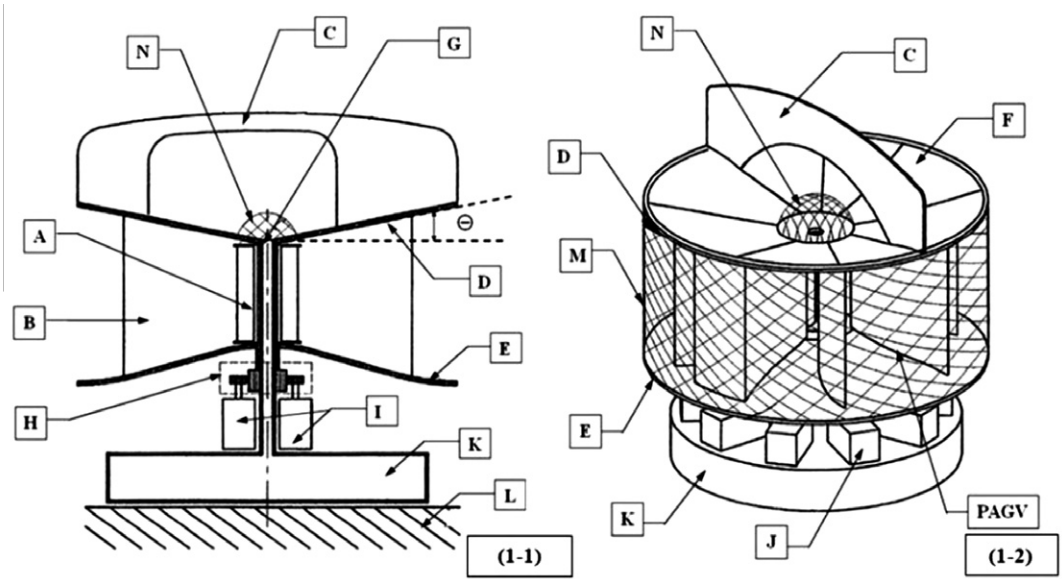


Fig. 1. General arrangement of the wind–solar hybrid energy system with rain water collection feature – (1–1) side sectional view; (1–2) perspective view [3].

research of renewable systems, the most notable shortcomings in evaluation of a wind–solar hybrid energy system that the literature survey reveals are as below:

1. Most of the investigations on the building integrated wind energy system were done on small scale systems. Large scale systems have still not been given attention enough to be placed in urban areas.
2. Low wind speed potential is the main difficulty to apply wind energy system in most of the regions. Augmenting the performance of the wind turbine can help to alleviate this problem.
3. Financial conditions of proposed configurations for solar and/or wind energy systems are a serious problem. A new combination of wind turbine and solar panels with additional energy efficient feature is needed to reduce the *LCC* of the hybrid system.

Nowadays, large-scale building integrated with wind turbine technology is rarely seen in major cities. Noise and vibration from wind turbines are among the greatest obstacles to integrating them into buildings. The Bahrain World Trade Center (BWTC) is the first large-scale integration of wind turbines in a building. The building consists of two 50-storey sail-shaped office towers which taper to a height of 240 m and support three 29 m diameter, 225 kW horizontal-axis wind turbines. However, having such large turbines so close to occupied spaces raise concerns about noise and vibration [28].

3. Design description of the system

The first modern concepts to integrate wind energy into buildings were introduced in the 1930s and 1940s in Germany. Hermann Honnef, a German engineer, stimulated some enthusiastic discussions about wind power and proposed the construction of a gigantic multi-rotor wind power tower, producing as much as 60,000 kW of power [29]. The design of Chong et al. [30] is also intended to integrate a hybrid wind–solar energy system on the top of a high-rise building with more emphasis on visual impact, safety, noise pollution and improvement on starting behavior of the wind turbine.

This patented design overcomes the inferior aspect of low wind speed by guiding (to obtain better flow angle of wind turbine blade) and increasing the speed of high altitude wind through the PAGV. The general arrangement of this system is shown in Fig. 1-1 and 1-2. The system can be of cylindrical shape or any shape of design, depending on the building architectural profile, such as in the shape of an ellipse, etc. The wind turbine, [A] is located in the middle of the system, surrounded by the PAGV. As safety is the main public concern, this design is safe in case of blade failure. Figs. 2 and 3 illustrate the artist's impression of the wind–solar hybrid with rain collector systems, which are being retrofitted on high-rise buildings. Peoples in the building will not notice the existence of the wind turbine because the system is placed on top of the building and wind turbine shadow flicker is also not a problem. This system seems to be more adaptable to be installed in urban areas compared to conventional wind turbine (without enclosure) and building permit might not be a problem.

The PAGV consists of an upper wall duct [D], lower wall duct [E] and guide vanes [B]. The PAGV is designed to be fixed or yaw-able with the help of a rudder, [C] or pressure sensors and servo-motor, to face the on-coming wind stream. The PAGV collects the wind stream radially from a larger area and creates a venturi effect to increase the wind speed before entering the wind turbine. The

Fig. 2. Artist's impression of the wind–solar hybrid renewable energy and rain water harvester retrofitted on top of some buildings in Kuala Lumpur, Malaysia [23].

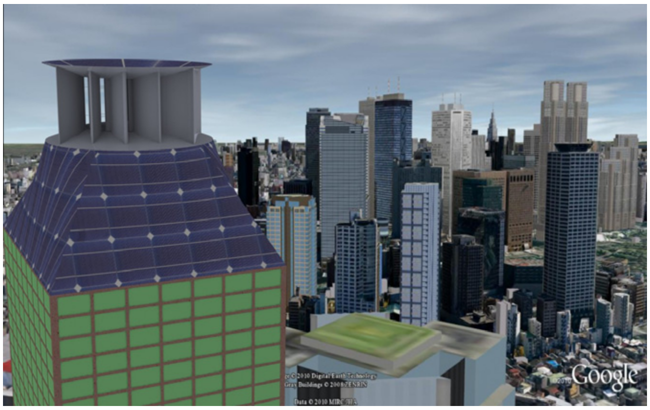


Fig. 3. Illustrative view of a high-rise building with the hybrid renewable energy system integrated on it. The background is a modified view of the Tokyo city by "Google Earth" software.

wind turbine can take the shape of any existing vertical axis or horizontal-axis wind turbine design or their combinations. The wind turbine has a common rotating axis with the PAGV. The centre drive shaft of the VAWT is coupled with the generator, [I] through the power transmission shaft and mechanical drive system, [H] such as a gear system. The PAGV consists of vanes of variable sizes or shapes having constant or varying thicknesses, in which they are positioned surrounding the turbine. The upper wall duct and lower wall duct are inclined at an angle, θ from the horizontal plane. The exterior surface of the upper wall of the PAGV provides the base for placement of solar panels, [F] or solar concentrator system. The rainwater flows through the rainwater passage, [G] in the middle of the system and is stored in the water storage compartment, [K] at the bottom thereby reducing the electrical power required to pump water to upper levels of the building. A rainwater mesh or filter, [N] prevents the flow of foreign objects into the passage which can cause blockage of the passage. The mesh, [M] is mounted at the entrance side of the PAGV to avoid foreign objects from striking the VAWT, e.g. bird-strike. The power generated from the wind turbine and solar panel is stored in a battery bank, [J] or fed into the electricity network line. A layer of thermal insulation, [L] is embedded at the bottom of the system to prevent heat transfer into the interior part of the building.

The use of VAWT in this system has tackled the concerns on noise and vibration produced by the HAWTs that are integrated with the Bahrain World Trade Center. VAWT produces much lower levels of noise and vibration compared to the HAWT because the blades do not stick out so far and so exert less pull [31]. In addition, since the VAWT is surrounded by the PAGV, the noise is minimized. The large size of the wind turbine may be able to produce a higher amount of power, but when the wind speed is low, the turbine works much lower than its rated power. For this system, the PAGV will help the smaller size of the VAWT (inside the PAGV) to spin close to its rated power even if the wind speed is low. On top of that, the smaller size of the wind turbine that is enclosed in the PAGV has lesser noise and vibration.

Besides all mentioned features, the system is also designed by taking into account the installation and maintenance stages. Components of the VAWT and PAGV are fabricated in feasible-to-carry forms (easy to dismantle and assemble) and are easily transported to the top of a high-rise building. For maintenance purposes, the system is accessible from the interior of the building. To prevent the motion of the VAWT during maintenance works, a locking device can be installed. The maintenance cost is expected to be the same as the current operating VAWT.

The system utilizes the advantages of the Malaysian climate, i.e. high solar radiation and high rainfall over a year for green energy generation and free water supply. To conduct the evaluation of this 3-in-1 combined system the meteorological data that were obtained from the Malaysian Meteorology Department was used. The data are from the weather stations in or near an urban area. The data consist of wind speed, solar radiation as well as rainfall, from year 2005 to 2007. Solar radiation data were obtained from the KLIA weather station located in Sepang and the wind data were measured at Petaling Jaya, Fig. 4. These data were utilized for analysis of variation of mean wind speed, solar radiation and amount of rainfall. The power or energy gained from these parameters can be subsequently predicted.

4. Methodology

The calculation of the energy output of the designed hybrid system was done based on its technical characteristics and actual weather data of wind speed, solar radiation and rainfall. Then, the economic and financing characteristics of Malaysia were included to evaluate the financial performance of the system.

4.1. Solar energy system

The integrated solar energy system that is considered here consists of a PV module array, hybrid charge controller and inverter (which are shared with the wind turbine). The PV modules are placed on the top of the PAGV. Based on the solar radiation data analyzed at the weather station located at KLIA in Sepang (Lat.: 2°44′N and Long.: 101°42′E), solar energy generation E_{solar} is estimated by the following equation:

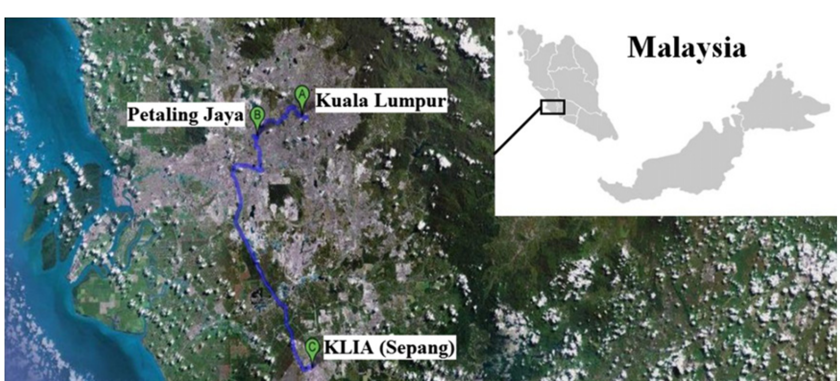
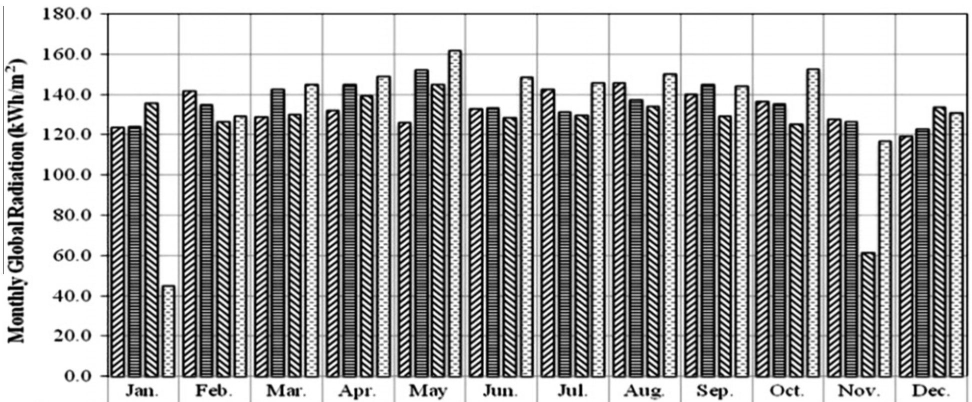


Fig. 4. Map of studied area in Malaysia.



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2006	123.9	141.9	129.2	132.2	126.3	133.2	142.5	145.7	140.2	136.6	127.8	119.4
2007	124.3	134.9	142.6	145.2	152.2	133.3	131.4	137.5	145.2	135.3	126.5	122.8
2008	135.9	126.6	130.2	139.5	145.1	128.6	129.6	134.1	129.5	125.3	61.4	133.9
2009	45.1	129.5	145.2	149.0	161.9	148.8	145.8	150.3	144.2	152.7	116.7	131.1

Fig. 5. Monthly global radiation in KLIA Sepang for years 2006–2009.

$$E_{solar} = G_s \cdot A_s \cdot \eta_{ps} \cdot K \quad (1)$$

where G_s is annual mean daily global irradiation (kW h m^{-2}/day), A_s is array active area (m^2), η_{ps} is PV module conversion efficiency and K is solar power loss. The meteorological data of this site for four years is shown in Fig. 5. It illustrates that the monthly global radiation is in the range of 120–140 kW h m^{-2}, with a daily solar radiation of 4.5–5.5 kW h m^{-2}. Therefore, there is a stable output of energy from this source.

A commercial monocrystalline silicon solar cell is chosen to convert solar radiation to electricity. Its specifications and estimated daily electrical energy generation are listed in Table 1. By selecting monocrystalline silicon PV modules with efficiency of 16.4%, the solar energy generation is approximately 108 MW h/year or 295.9 kW h/day.

4.2. Wind energy system

The wind data are obtained from the meteorological station at Petaling Jaya (Lat.: 3°06′N and Long.: 101°39′E) which is an urban area in Malaysia. Meteorological data at this site is recorded from 2006 until the end of 2009. The height of the wind sensor above ground level is 46.2 m (height of wind sensor above mean sea level: 60.8 m). As illustrated in Fig. 6, the mean monthly wind speed is calculated (from hourly average wind speed data) and shown in the graph. This graph shows that the main portion of the wind speeds are in the range of 1.5–2 m/s.

From the analyzed data at the Petaling Jaya weather station, the wind speed is less than 4 m/s for more than 90% of the total hours in a year. As mentioned before, the system was assumed to be installed on the top of a high-rise building in an urban area (Petaling Jaya), where the height of the building is 220 m. The wind shear boundary layer causes the wind speed to increase with height in accordance to the following equation:

$$V(z) = V_r(z/z_r)^{\alpha} \quad (2)$$

where $V(z)$ is wind speed at height z, V_r is wind speed at the reference height z_r above the surface, and α is wind friction coefficient which depends on the roughness of the terrain and the stability of the atmosphere [32]. Thus, for a typical urban area like Petaling Jaya, the value of $\alpha = 0.4$. In this case study a high-rise building with the height of 220 m was taken as reference, and the wind speed at this height was calculated based on Eq. (2), Fig. 7. The wind speed is calculated to be approximately 1.8 times higher than the wind speed at reference height of 46.2 m.

A comparative study by Eriksson et al. has shown that VAWTs are advantageous compared to HAWTs in several aspects. Generally, the VAWTs have the advantages such as ease of installation and maintenance (due to the generator being located beneath the turbine), omni-direction wind power extraction and no yawing mechanism is required. In comparison between H-rotor and Darrieus turbines, H-rotor seems more beneficial than the Darrieus. The possibility of simple structure and lower level of maintenance are the strength of the H-rotor turbine [33].

The variation in wind speed can be described by the Weibull probability distribution function (h) with two parameters, the scale parameter (c) and the shape parameter (k). The probability of wind speed (V) in an interval of time is obtained by the following [32]:

$$h(V) = (k/c) \cdot (V/c)^{k-1} \cdot e^{-(V/c)^k} \quad (3)$$

Wind power is proportional to the cube of the speed, and the energy collected over the year is the integral of $h \cdot V^3 \cdot dV$. Therefore, root mean cube (rmc) speed is defined in a manner similar

Table 1
Solar cell specifications and estimated solar energy generated at KLIA weather station, Sepang (year 2007).

Peak power	160 W
Maximum voltage	23.32 V
Maximum current	6.86 A
Open-circuit voltage	28.89 V
Short-circuit current	7.34 A
Module typical performance data	
Estimated PV module conversion efficiency, η_{ps}	16.40%
Estimated power/performance efficiency, K	80%
Power density	**48.99** W/m^2
Module and cell dimensions and specifications	
Dimensions of module (single)	0.66 × 1.5 m^2
External cell area	0.0275 m^2
Estimated percentage of cell active area	68%
Estimated cell active area	0.0187 m^2
PAGV top surface area	700 m^2
Estimated total active area, A_s	476 m^2
No. of module	707
Estimated solar energy generation per day = $G_s \cdot \eta_{ps} \cdot K \cdot A_s$	**295.9** kW h

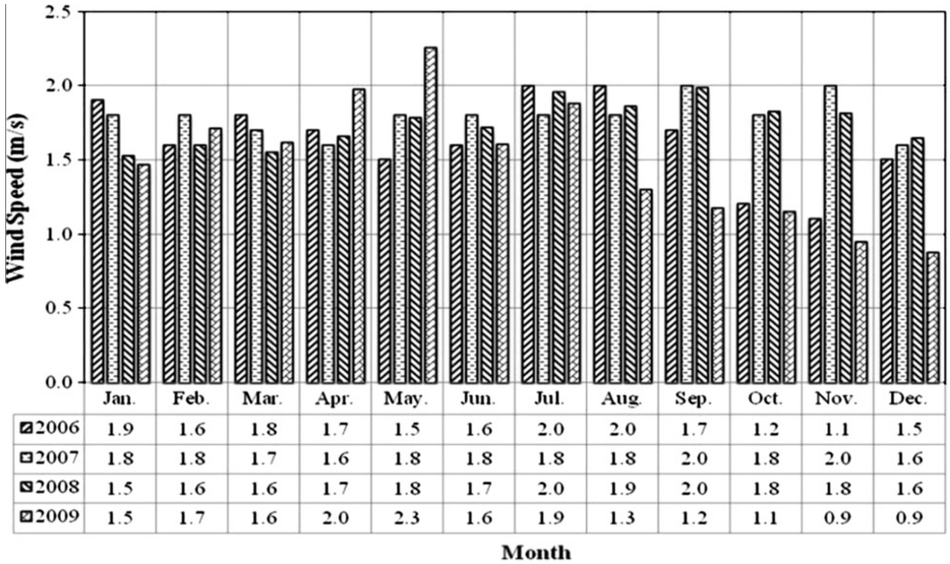


Fig. 6. Mean monthly wind speed at the height of 46.2 m above ground level (in Petaling Jaya) for years 2006–2009.

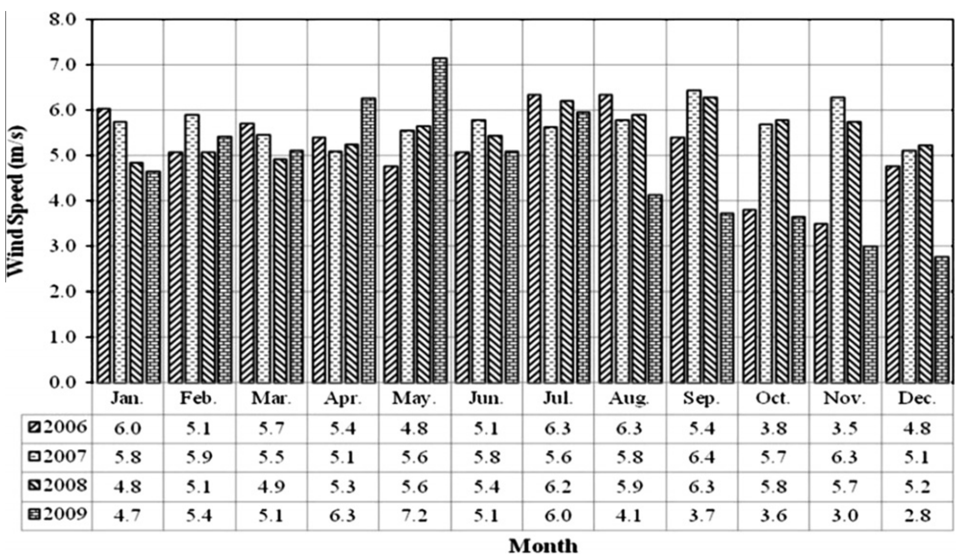


Fig. 7. Calculated mean monthly wind speed at the height of 220 m above ground level (in Petaling Jaya) for years 2006–2009.

to the root mean square (*rms*) value in alternating current (AC) electrical circuits. The *rmc* equivalent of the digital data logging is as follows:

$$V_{rmc} = \sqrt[3]{1/n \sum_{i=1}^{n} V_i^3} \quad (4)$$

where n is the number of the digital data. The *rmc* speed is useful in quickly estimating the annual energy potential of the site. By using V_{rmc}, the average power density is given by:

$$P_{rmc} = 1/2n \sum_{i=1}^{n} \rho \cdot C_p \cdot \eta_{\mathrm{tr}} \cdot \eta_g \cdot \eta_{\mathrm{PAGV}} \cdot A \cdot V_{rmc}^3 \quad (5)$$

Then, the annual energy production potential of the site is obtained by multiplying the P_{rmc} value by the total number of operating hours in the year.

H-rotor was chosen due to the advantages of blade profile, noise, generator position and self-starting behavior. The technical characteristics of a commercial VAWT are shown in Table 2. The operating wind speed of turbine is in the range of 3–25 m/s. The wind speed is increased about 1.7 times after passing through the PAGV [34]. With the estimated efficiency of the sub-systems

Table 2
Specifications of the VAWT.

Manufacturer	Shanghai **MUCE** Wind Power Equipment Co. Ltd.
Starting wind speed	1.8 m/s
Working wind speed	3.0–25 m/s
Rated wind speed	12 m/s
Maximum wind speed	63 m/s
Swept area (diameter × height), A	17 m × 9 m
No. of blades	4
Generator efficiency, η_G	0.8
Efficiency due to PAGV loss, η_{PAGV}	0.9
Efficiency due to bearing and transmission loss, η_{TR}	0.9
Rotor efficiency, C_p	0.4
Air density, ρ	1.201 kg/m^3
Estimated wind energy generation per day $= 0.5 \cdot \rho \cdot C_p \cdot \eta_{\mathrm{TR}} \cdot .\eta_{\mathrm{G}} \cdot \eta_{\mathrm{PAGV}} \cdot A \cdot V_i^3$	**236.2** kW h

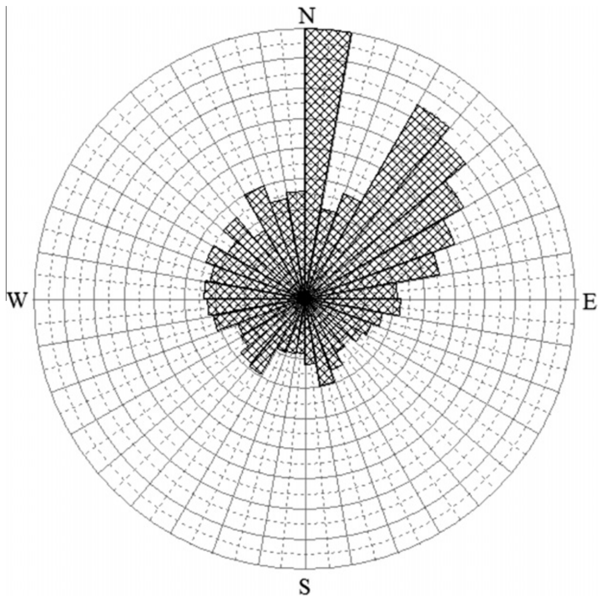


Fig. 8. Wind direction frequency in Petaling Jaya (year 2008 and 2009).

or components, the wind energy generation from a system (30 m × 14 m for PAGV, 17 m × 9 m for VAWT) installed on the top of a building of 220 m height is calculated to be approximately 86.2 MW h/year or 236.2 kW h/day.

Based on the weather data for the years 2008 and 2009, the frequency of wind direction is obtained and shown in Fig. 8. The data illustrates that the variation of wind direction is mainly between 120° and 180°. As was mentioned earlier, the PAGV is built on top of high-rise buildings and is designed to be yaw-able. So, the PAGV will yaw to face the direction of the wind.

4.3. Rain water collection system

One of the energy consumption sources in a high-rise building is pumping water to the top levels of a building. By collecting data on rainfall for eight years (2002–2009), it became obvious that there would be a significant amount of rainfall annually in the evaluated site, i.e. Petaling Jaya. So, investing on rainwater harvesting would be reasonable. Table 3 shows the annual rainfall at Petaling Jaya (2002–2009) in 1 m^2. The volume of rainwater collected V_{rain} (for catchment area of 700 m^2), is estimated by using Eq. (6), (Rational equation):

$$V_{rain} = A_c \cdot I \cdot C_r \tag{6}$$

where A_c is rain catchment area (m^2), I is the rainfall intensity (mm/month) and C_r is the runoff coefficient (assumed as 0.75). To calculate energy savings by collecting rainfall on the top of the building Eq. (7) need to be used:

$$E_{rain} = \rho \cdot V_{rain} \cdot g \cdot h \cdot (2.778 \times 10^{-4}) \tag{7}$$

where ρ is water density, g is gravity, h is the height of building and (2.778×10^{-4}) is the conversion factor of joule to watt-hour.

Table 4
Annual energy generated or saved in Petaling Jaya.

Energy source	Solar (energy generation)	Wind (energy generation)	Rainwater (energy saving)	Total
Energy generated/saved (kW h/year)	108,000	86,200	1025	**195,225**

Rainfall data for the years 2002–2009 are analyzed and results for mean monthly rainfall volume and energy savings are tabulated in Table 3. Based on the data analyzed in Petaling Jaya area, the estimated monthly rainwater collected in the roof area of 700 m^2 is 143 m^3. Thus, energy used to pump this amount of water to the top of a 220 m high building is about 1025 kW h/year.

As a summary, energy generation and savings by this system in a year is tabulated in table 4:

4.4. Economic assessment

The electricity generated by the proposed hybrid wind–solar–rain system is fed into the urban electricity network (Fig. 9). For the economic analysis of the proposed hybrid system, the *LCC* method is used and it takes into consideration the complete range of costs and makes cash flows time-equivalent.

Wind–solar–rain savings (*WSRS*) is the difference of the cost of a unit of produced energy (*CUE*) and commercial tariff rate (*CTR*) of electricity which is given in kW h by:

$$WSRS = CTR - CUE \tag{8}$$

The mortgage payment consists of principal payment and interest of money on the loan borrowed for system installation. To keep the system in operation condition some periodic costs such as operation and maintenance needed to be paid. Income tax savings for the system can be stated as [35]:

$$ITS = ETR \times (IP + PT) \tag{9}$$

The present worth factor (*PWF*) is included in the calculation to determine the entire gain of the system. If a payment repeats every year and inflates at a rate of i per annum, *PWF* of the payments is obtained by the following equation:

$$PWF(N, i, d) = \sum_{j=1}^{N} (1+i)^{j-1}/(1+d)^{j} \tag{10}$$

where N is the period of economic evaluation. The inflation and discount rates are represented by i and d, respectively. Then, to determine the present value (*PV*) of payment or income for Nth period (usually year) in the future, the following equation is used:

$$PV = 1/(1+d)^{N} \tag{11}$$

PV is used to return the value of the future payments or incomes on a given period to present value. Then, the net present value (NPV) is calculated to obtain the sum of the present values of the individual cash flow.

Table 3
Mean monthly rainfall and energy savings (water pumping) at the height of 220 m in Petaling Jaya (Years 2002–2009).

Month	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Rainfall (mm)	215	196	330	426	190	265	196	158	260	296	437	296	3265
Volume (m^3)	113	103	173	224	100	139	103	83	137	155	229	155	1714
Energy (kW h)	67	62	104	134	60	83	62	50	82	93	137	93	***1025***

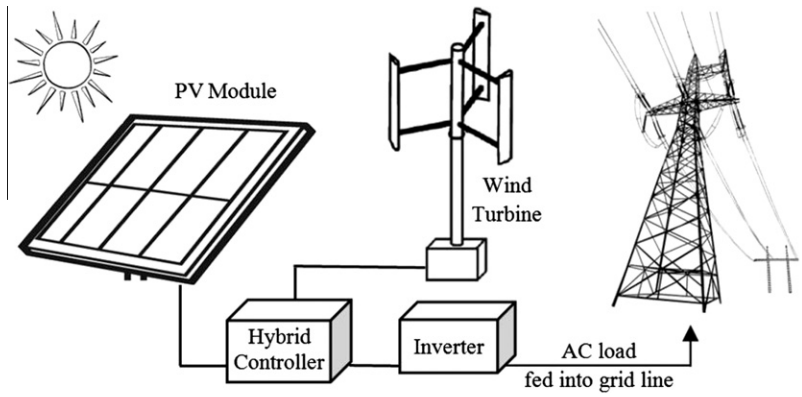


Fig. 9. Schematic of the wind–solar hybrid energy system.

5. Results and discussion

5.1. The effect of the PAGV on the performance of the system

The advantages of integrating the PAGV into an existing wind–solar system are illustrated and compared with similar characteristics of the system without the PAGV. The operating time and extractable energy of the wind turbine increase with the implementation of the PAGV. Therefore, it affects initial capital and payback time of the system. Based on the original specifications of the selected wind turbine, the minimum operating wind speed is 3.0 m/s. The average of operating hours and energy generation of this site in years 2007–2009 is tabulated in Table 5. The analysis is done based on the operating wind speed in the range of 3–25 m/s. On average, the number of operating hours increases about 57.6% when the PAGV is applied. Likewise, energy generation increases by about 327%.

5.2. Financial evaluation

The annual energy generated and saved by this wind–solar hybrid energy generation system and rain water collector in a site around Petaling Jaya is estimated to be 195.2 MW h. According to the annual report published by Tenaga Nasional Berhad (TNB) in year 2009, the average annual electric energy consumption per unit domestic customer in Malaysia is approximately 2.86 MW h [36]. This amount of saved energy is sufficient to supply about 68 units of domestic customer.

The whole system is estimated to cost about USD$600,240 with 10% down payment is made. The rest of the capital is financed in a period of 25 years at an interest rate of 7%. It is expected to pay general operation and maintenance costs for components of the system annually with an inflation rate of 4% [37]. Energy pricing mechanism in Malaysia is a combination of market-driven and regulated prices [38]. The commercial tariff of electricity, provided by TNB is $0.113/kW h [39]. According to the electricity price trend, tariff rate is predicted to rise by 10% annually. The extra property tax is 2% of the initial capital. Operation and maintenance costs for PV panels and wind turbine are estimated to be $0.001 and $0.011 per kW h respectively [40,41]. Details of these costs, maintenance and economic parameters are shown in Table 6 and 7.

Inverters and hybrid controllers need to be replaced after certain periods of time and are much more expensive than to be included into the maintenance annual fee. They are expected to be replaced every five years. Their price is estimated to increase by 4% annually. The effective income tax rate is estimated to be 45% through the life cycle.

The NPV of the energy system over a 25-year period is $29,528 at the market discount rate of 8%. Financial calculations are shown

Table 5
The average of annual operating hour and energy generation of wind turbine in Petaling Jaya (z = 220 m) for years 2007–2009.

	Number of operating hours	Energy generation (MW h)
Without PAGV	4049	20.2
With PAGV	6383	86.2
Increment percentage	*57.6%*	*327%*

Table 6
System components price.

Item	Cost
Photovoltaic array	
PV panel	$226,240.00
Estimated installation	$3000.00
Wind system	
H-rotor wind turbine	$223,280.00
PAGV construction	$50,000.00
Yawing mechanism	$55,000.00
Inverter	$$15,200.00
Hybrid controller	$12,520.00
Rainwater collector	$15,000.00
Estimated capital cost	**$600,240.00**
Operation and maintenance (O&M)	
PV O&M cost per kW h ($/kW h)	$0.001
PV O&M cost per day	$0.296
Wind turbine O&M cost per kW h ($/kW h)	$0.011
Wind turbine O&M cost per day	$2.598
Yaw mechanism O&M (yearly)	$1000.00
Estimated annual O&M costs	**$2050.00**

Table 7
Economic parameters.

Item	Value
Electricity price (per kW h)	$0.1134
Down payment	10%
Inflation rate of electricity price	10%
Inflation rate of controller price	4%
Inflation rate of inverter price	4%
Inflation rate of operation and maintenance	4%
Inflation rate of extra property tax	4%
Interest rate of principal	7%
Discount factor	8%
Extra property tax (percentage of principal)	2%

Table 8
The economic analysis of the hybrid energy system (in US$) for Petaling Jaya (25-year life cycle).

Year	Energy generation (kW h/year)	Cost of energy ($)	Extra mortgage payment	Interest in year	Principal payment	Principal balance	Inverter replacement	Controller replacement	Maint. and oper.	Extra property tax	Income tax savings	WSR savings	PV of WSR savings	Cum. WSR savings	Cum. energy cost savings
0						540,216						(60,024)	(60,024)	(60,024)	–
1	195,220	22,138	(46,355)	37,815	8539	531,677	–	–	(2050)	(12,005)	22,419	(15,852)	(14,678)	(75,876)	22,138
2	195,220	24,352	(46,355)	37,217	9137	522,539	–	–	(2132)	(12,485)	22,366	(14,254)	(12,220)	(90,130)	46,490
3	195,220	26,787	(46,355)	36,578	9777	512,763	–	–	(2217)	(12,984)	22,303	(12,466)	(9896)	(102,597)	73,277
4	195,220	29,466	(46,355)	35,893	10,461	502,301	–	–	(2306)	(13,504)	22,229	(10,470)	(7696)	(113,067)	102,742
5	195,220	32,412	(46,355)	35,161	11,193	491,108	(18,493)	(15,232)	(2398)	(14,044)	22,142	(41,968)	(28,563)	(155,034)	135,154
6	195,220	35,653	(46,355)	34,378	11,977	479,131	–	–	(2494)	(14,606)	22,042	(5759)	(3629)	(160,793)	170,808
7	195,220	39,219	(46,355)	33,539	12,815	466,316	–	–	(2594)	(15,190)	21,928	(2992)	(1746)	(163,784)	210,026
8	195,220	43,141	(46,355)	32,642	13,712	452,603	–	–	(2698)	(15,797)	21,798	89	48	(163,696)	253,167
9	195,220	47,455	(46,355)	31,682	14,672	437,931	–	–	(2806)	(16,429)	21,650	3515	1759	(160,180)	300,622
10	195,220	52,200	(46,355)	30,655	15,699	422,231	(22,500)	(18,533)	(2918)	(17,087)	21,484	(33,707)	(15,613)	(193,888)	352,822
11	195,220	57,420	(46,355)	29,556	16,798	405,433	–	–	(3035)	(17,770)	21,297	11,558	4957	(182,330)	410,242
12	195,220	63,162	(46,355)	28,380	17,974	387,459	–	–	(3156)	(18,481)	21,088	16,258	6456	(166,072)	473,404
13	195,220	69,478	(46,355)	27,122	19,232	368,226	–	–	(3282)	(19,220)	20,854	21,476	7897	(144,596)	542,883
14	195,220	76,426	(46,355)	25,776	20,579	347,648	–	–	(3413)	(19,989)	20,594	27,263	9282	(117,332)	619,309
15	195,220	84,069	(46,355)	24,335	22,019	325,628	(27,374)	(22,548)	(3550)	(20,788)	20,306	(16,241)	(5120)	(133,573)	703,378
16	195,220	92,476	(46,355)	22,794	23,561	302,068	–	–	(3692)	(21,620)	19,986	40,796	11,908	(92,778)	795,853
17	195,220	101,723	(46,355)	21,145	25,210	276,858	–	–	(3840)	(22,485)	19,633	48,678	13,156	(44,100)	897,577
18	195,220	111,896	(46,355)	19,380	26,975	249,883	–	–	(3993)	(23,384)	19,244	57,408	14,366	13,308	1009,472
19	195,220	123,085	(46,355)	17,492	28,863	221,021	–	–	(4153)	(24,320)	18,815	67,073	15,542	80,381	1132,557
20	195,220	135,394	(46,355)	15,471	30,883	190,138	(33,305)	(27,433)	(4319)	(25,292)	18,344	17,034	3655	97,414	1267,951
21	195,220	148,933	(46,355)	13,310	33,045	157,093	–	–	(4492)	(26,304)	17,826	89,609	17,801	187,023	1416,884
22	195,220	163,826	(46,355)	10,996	35,358	121,735	–	–	(4671)	(27,356)	17,259	102,703	18,891	289,726	1580,710
23	195,220	180,209	(46,355)	8521	37,833	83,901	–	–	(4858)	(28,450)	16,637	117,183	19,958	406,909	1760,919
24	195,220	198,230	(46,355)	5873	40,481	43,420	–	–	(5053)	(29,588)	15,958	133,192	21,004	540,101	1959,149
25	195,220	218,053	(46,355)	3039	43,315	105	–	–	(5255)	(30,772)	15,215	150,887	22,032	690,988	2177,202
												Sum	*29,528*		

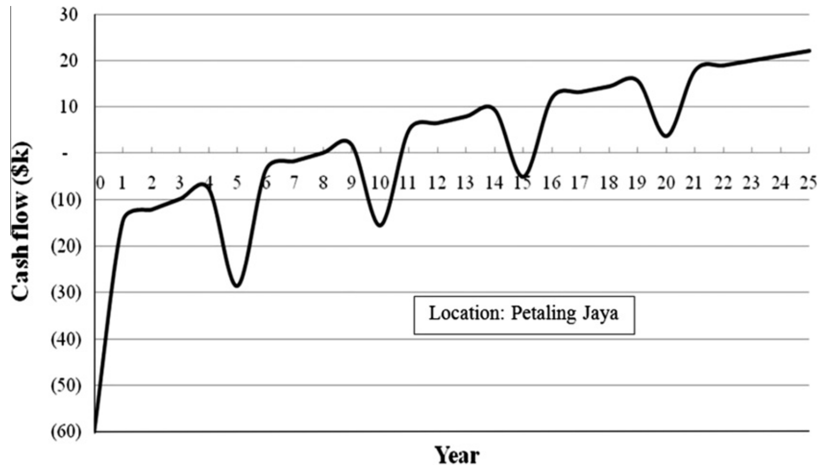


Fig. 10. The annual present value of the system savings over the economic analysis period (25-years life cycle cost analysis).

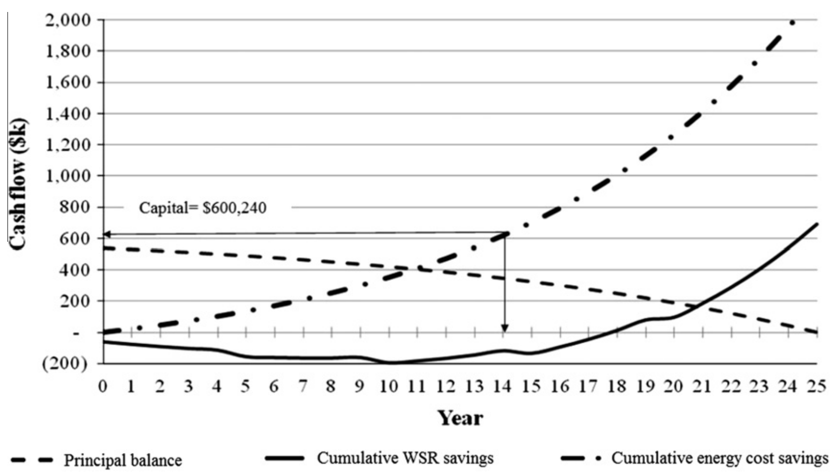


Fig. 11. Changes in principal balance, cumulative WSR savings and cumulative energy cost savings as a function of time through the 25-years life cycle cost analysis.

in Table 8. The sum of the yearly present value of the wind–solar–rain system is the NPV of the gains from this hybrid system. A remarkable portion of the energy demand of a high-rise building could be supplied by this innovative hybrid energy system. Economic analysis of this system shows that for the first time at year 8, cash flow becomes positive. But, because of the replacement of hybrid controller and inverter it turned negative for some years after that. After year 15 the cash flow becomes positive forever (Fig. 10). So, it shows the effect of the PAGV in improving the performance of this hybrid energy system. By improving the efficiency of this system, it will become more economical. Based on recent policy by the government in Malaysia about feed-in tariff (FIT) for renewable energy to enable users to sell excess power to the power grid, generated energy by renewable sources will be purchased in higher price than the selling price [42]. However, none of these subsidies are included in this analysis. Payback time is defined in many ways. Below, some information that can be extracted from Table 8 and Fig. 11 are listed:

(a) The cumulative energy cost savings ($619,309) exceeds the initial capital in year 14.
(b) The cumulative WSR system savings turns positive by year 18.
(c) The cumulative WSR system savings ($187,023) exceeds the remaining principal balance ($157,093) by the end of year 21.

6. Conclusion

In this paper, a techno-economic analysis has been carried out on an innovative wind–solar hybrid renewable energy generation system with rainwater collection feature for urban high-rise application. Technical viability of the system shows that by integrating the available technologies of wind turbine, PV panels and rainwater collector with the PAGV, this system can cover a significant portion of a building's energy demands and helps to make the building independent (or partially independent) from the urban electricity grid. The analysis shows that for a system with the PAGV (30 m diameter and 14 m high) and an H-rotor VAWT (17 m diameter and 9 m high) mounted on the top of a 220 m high building in Petaling Jaya, the estimated annual energy savings is 195.2 MW h/year. The importance of the PAGV is determined by comparing the system performance with another system which is technically similar but without the PAGV. There was a 327% increase in energy generation when the PAGV is applied. The PAGV also improves the starting behavior and prolongs the operating hour of the wind turbine. Economic analysis shows that manufacturing, operation and maintenance costs of the system are covered in the lifetime of the system. For this project, the NPV is $29,528 for the 25-years lifetime.

This design is a reliable model for large scale systems placed in urban areas. The configuration solves or alleviates several problems of wind–solar energy systems such as safety, visual impact, noise pollution and response to the wind. It is placed on top of a high-rise building to prevent any disturbance to surrounding. In addition, augmenting the performance of the wind turbine can help to address low wind speed potential of this site. Based on the new FIT mechanism for green energy generation in Malaysia, there will be a considerable reduction in the payback period of initial investment and a significant incentive for the private sector to invest in renewable energy systems. Since the selected site for this study is situated at low wind speed region, shorter payback period can be expected for sites with higher wind speed.

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