Early development of an innovative building integrated wind, solar and rain water harvester for urban high rise application

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An innovative 3-in-1 wind–solar hybrid renewable energy and rain water harvester is designed for urban high rise application. A novel power-augmentation-guide-vane (PAGV) that surrounds the Sistan rotor vertical axis wind turbine (VAWT) is introduced to guide and increase the speed of the high altitude free-stream wind for optimum wind energy extraction. The system was also designed to provide optimum surface area and orientation for solar power generation. On the top surface of the PAGV, rain water can be collected, thereby reducing the electrical power required to pump water to the upper levels of the high rise building. To minimize the visual impact, the outer design of the PAGV can be blended into the building architecture. The system is also designed to eliminate the bird-strike problem and the concern on safety, and reduce the vibration. Wind tunnel testing on the scaled down prototype shows that the PAGV improved the starting behavior and increased the rotational speed of the Sistan rotor VAWT by 73.2% at the wind speed of 3 m/s. According to the present study, with the 30 m diameter and 12 m high PAGV integrated system, the estimated annual energy generated and savings is 160 MWh.

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1. Introduction

Recently, the negative effects of pollution caused by fossil fuel power generation have urged the importance of developing clean energy generation. Thus, it is beneficial to the society to promote green and sustainable energy usage in our daily lives to overcome the finite character of fossil fuels. Many studies have recognized wind and solar energy as potential sources of free, clean and inexhaustible energy. Energy generation from both solar and wind energy requires no usage of water, thus they would not bring out the environmental concerns, i.e. water crisis problem, compared to energy generation from other sources such as hydro, biomass and nuclear.

Malaysia is situated at the equatorial zone, and experiences low speed winds (doldrums) consisting of Southwest and Northeast Monsoons in a year. Most of the areas in mainland experience low (free-stream wind speed, \( V_{\infty} < 4 \) m/s for more than 90% of total wind hours) and unsteady wind speeds. As a result, most of the existing wind generators (rated wind speed, \( V_{\text{rated}} = 9–15 \) m/s) are not suitable for Malaysian applications since they are designed for high wind speeds. Based on the study conducted by Chong [1], wind energy in Malaysia can only be an economically viable generation of electricity for isolated areas far away from the national grid system. Meanwhile; in Europe, due to the decreasing number of economic sites, organizations involved in planning are urged to place wind turbines closer to populated areas [2]. In order to design a wind energy generation system that can be used in urban areas, there are barriers which must be considered such as acoustic pollution, structural issues, safety problems, blade failures, electromagnetic interference and visual pollution [3,4].

There are several possibilities whereby wind energy generation systems can be integrated into urban environments and they can be categorized into three types [5]:

(a) Siting stand-alone wind turbines in urban locations.
(b) Retrofitting wind turbines onto existing buildings.
(c) Full integration of wind turbines together with architectural form.

For the first option, it may encounter constrains of limitation of land in urban area and low wind speed due to other existing high rise buildings. It may also give rise to public concern over safety, issues of noise and visual impact. For the second approach, small-scale turbines are easily viable as a building retrofit solution and these micro-wind turbines in various types are commercially available [6]. The government of UK provided attractive schemes which...
accounted for approximately 17% of state grant aid to encourage the application of micro-wind turbines in urban area [7]. However, such small-scale wind turbines for building integration may not always be aesthetically pleasing and also hazardous due to turbine blades failures occurring. For retrofitting wind turbine into existing building, there is an obvious difference in visual impact between the conventional wind turbine and the one that is specially designed for urban area as illustrated by Sharpe and Proven [8]. The third strategy of a fully integrated solution involves a well-defined construction plan and huge capital. A matrix of generic options for integrating wind turbines into the building was developed during the initial phase of the project [5]. It might seem fascinating from both the architectural and aerodynamics point of view. However, the issues of safety, noise, vibration and visual impact should not be underestimated.

2. Building integrated wind turbines

Building integrated wind turbines are gaining more attention for urban on-site clean energy generation. 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 [9]. The factors that influence the decision to build a building integrated wind turbines are the positioning (height above roof ridge and position relative to the prevailing wind direction), the urban terrain roughness and the adjacent buildings that can cause wind shadow [10].

The large-scale building integrated wind turbines have been demonstrated in some countries. These buildings have been established as iconic buildings. The first large-scale integration of wind turbines with a building is the Bahrain World Trade Center. This 240 m high building harmoniously integrates building augmented design with three horizontal axis wind turbines of 29 m diameter [11]. The Strata Tower in London was built to incorporate wind turbines within its structure. The three wind turbines at the top of the building are rated at 19 kW each and are anticipated to produce 8% of electricity needed by the building [12]. In Guangzhou, China; the Pearl River Tower was designed to harness the energy from solar and wind to sustain the building. The wind is flueed down from the vertical face of the tower toward a series of wind turbines for energy generation [13].

With further consideration of building and architectural integration, Müller et al. [14] has proposed and architecturally demonstrated a wind energy converter with a cylindrical form to facilitate current building design. Grant et al. [15] also reported and concluded that ducted wind turbines which are attached to the building roof have a significant potential for retrofitting into a building with small concern of visual impact. A concept and early development of the wind turbine called Crossflex utilized an existing Darrieus turbine concept, but it was applied in a novel form for building integration [8].

The demonstrative study for the wind and solar power hybrid system from Ashikaga Institute of Technology in Japan shows that the generated power by photovoltaic cells is abundant in the summer season and that by wind powered generator increases from autumn to winter. Thus, in the Ashikaga area, the utilization of wind energy is not promising in the summer season compared to solar energy. Consequently, the stable power output could be expected by the above-mentioned seasonal complementary relationship between the solar and wind energy after 1-year operation of the system [16].

As a result, an innovative design of power-augmentation-guide-vane (PAGV) to integrate several green elements (urban wind turbine, solar array for electricity and hot water, and rain water collector) is introduced [17]. It is compact and can be built on the top (or between upper levels) of high rise buildings or structures in order to provide on-site green power to the building. Besides, this system can be used in remote and urban areas of both low wind speed and high wind speed regions. This system also fully utilizes the advantages of Malaysian climate, i.e. high solar radiation and high rainfall for green energy generation and free water supply. Consolidation of the hybrid system as part of building architecture without negative visual impact definitely overcomes the barriers of implementing building integrated renewable energy system.

3. Novel design of the wind, solar and rain water harvester

3.1. General arrangement and working principle of the design

The patented design of this wind, solar and rain water harvester integrates and optimizes several green technologies; including urban wind turbine, solar array and rain water collector [17]. Fig. 1
shows the general arrangement of this innovative system. The geometry of the system depends on the building architecture profile, thus the system can be in cylindrical shape or any shape of design. The wind turbine [A] is located in the middle of the system, surrounded by the PAGV. Hence, the wind turbine can take shape of any existing vertical axis wind turbine (VAWT) design or their combinations. However, an H-rotor VAWT is preferable.

The PAGV is designed to be fixed or yaw-able to face the oncoming wind stream with the help of a rudder [C] or pressure sensors and servo-motor. The PAGV consists of an upper wall duct [D], lower wall duct [E] and guide vanes [B]. The upper wall duct and lower wall duct are inclined at an angle, \( \theta \) from the horizontal plane. The PAGV consists of vanes in variable sizes or shapes having constant or varying thickness, in which they are positioned surrounding the turbine. The vanes form multiple flow channels which are utilized to speed up the wind stream by creating a venturi effect and to guide the wind stream to the optimized angle of attack of the VAWT blades.

The exterior surface of the upper wall of the PAGV provides the base for the placement of solar panels (solar photovoltaic and/or solar thermal panel) [F] or solar concentrator system. The solar panel can be fixed or pivoted with a solar tracking system. At the same time, these inclined solar panels also form the flow path for guiding the rain water toward the center of the system. The rain water then flows through the rain water passage [G] in the middle of the system. The rain water can be stored in the water storage compartment [K] at the bottom. A rain water filter [N] prevents the flow of foreign objects into the passage which can cause blockage of the passage.

In addition, the mesh [M] is mounted at the entrance side of the PAGV to prevent foreign objects from striking the VAWT. The center drive shaft of the VAWT can be coupled directly to the generator [I] or through the power transmission shaft and mechanical drive system [H] such as the gear system. The power generated from the wind turbine and solar panel is stored in a battery bank [J] or fed into the electricity grid line. At the bottom of the system, a layer of thermal insulation [L] is embedded to prevent heat transfer into the interior part of the building.

### 3.2. Features and configurations of the system (benefits and applications)

The features in this patented system are designed and integrated to harvest wind energy, solar energy and rain water. The PAGV collects the wind stream radially from a larger area and creates a venturi effect to guide and increase the wind speed before interacting with the wind turbine. In addition, it also reduces the turbulence. The VAWT [A] and the PAGV can also be built in multiple layers, by stacking them up vertically on top or between the upper layers of the buildings or structures. Fig. 2 shows a tandem design of a two-layered wind turbine and guide vane, the upper PAGV channels wind to the upper wind turbine while the lower PAGV channels wind to the lower wind turbine. Various innovative arrangements can be applied into the system; the upper and lower wind turbine can be connected to a common power-transmission shaft, gear system and generator, or in a separate manner. In the first design, both the upper and lower wind turbines are designed to rotate in the same direction, thus it can be coupled to the same power-transmission shaft or in the other way with different generators. For the second design, the upper and lower PAGV is designed to guide the wind in opposite directions. Besides, the wind turbines on adjacent layers too are designed to rotate in a contra rotating motion (to create a balanced-force between these two VAWTs) and each of them is coupled with their own generator. In addition, contra rotating motion is advantageous in reducing vibration and mechanical noise [18]. For the third design, the PAGV is similar to the previous design, but the wind turbines are mounted on two co-axial output shafts, which rotate in opposite directions. One of the output shafts can be coupled to the rotor of the generator and the other one to the stator of a generator to improve the relative angular velocity. A multi-stage generator can be matched to the PAGV integrated VAWT system. When the wind speed is below a speed threshold, only the first stage of the generator is engaged. When the wind speed increases and is above a speed threshold the second stage generators are engaged, and so on. A high wind speed cut-off system is activated to cut off the generator to prevent damage due to strong winds.

The VAWT [A] is enclosed by the PAGV and wind inlet mesh [M] as safety is the main public concern. There is no possibility for the blades to fly-off in case of blade failure and cause injury to the people around. The mesh mounted at the entrance of the PAGV can also prevent bird strike problem. The design solves most of the problems in locating wind turbines in urban and sub-urban areas. By inducting higher wind speeds into the VAWT, smaller and lighter rotating parts of the VAWT can be used for the same power output, which means lesser load on the bearing of turbines and reduced moment of inertia for better starting behavior. Smaller parts will also result in lower material, manufacturing and installation costs. The rotating blades of the wind turbine could produce the electromagnetic wave interference when the blades swing and “cut” the traveling wave. Greater interference occurs with large wind turbine blades and for metallic rather than composite material [19]. Compared to a conventional horizontal axis wind turbine with long blades, the VAWT in this invention has a smaller rotating body contained within an enclosure that is able to reduce electromagnetic interference. The noise level of the system or noise pollution is expected to be reduced since the wind turbine is enclosed in the PAGV. The system can also be equipped with shutter at the inlet of the PAGV to prevent the VAWT from over speeding when the wind speed is too high by controlling the amount of air intake.

The shape of the PAGV has an added advantage for solar panel installation. Besides being one of the main components in the PAGV that helps to improve the VAWT performance, the guide vanes and upper wall also serve as a supporting structure for solar panels. The solar panels that are arrayed on top of the PAGV become a catchment area for rainfall. The installation of this PAGV integrated system on the roof top space to collect wind and solar energy would maximize the amount of on-site energy generation instead of the space being occupied by solar panels only. Thus, this compact design is able to harvest more energy per area without the need of additional structure for solar panels and rainwater collection.

**Fig. 2.** Tandem design of a two-layered wind turbine and guide vane.
4. Wind tunnel testing of the PAGV prototype

4.1. Prototype fabrication and experimental set-up

A scaled down prototype (Fig. 4) of the PAGV was built to be integrated with a VAWT for wind tunnel testing. The wind tunnel testing was carried out to study the feasibility of integrating the VAWT with the PAGV in order to improve the performance of the wind turbine (to achieve higher rotational speed) in a controlled environment. A drag-type VAWT, i.e. 3-bladed Sistan rotor with 0.5 m diameter and 0.25 m high was chosen for the testing. The PAGV prototype was 2 times larger than the size of the Sistan rotor.

The wind tunnel tests were conducted for two configurations as follows:

(a) Sistan rotor without PAGV on top of the “building”.
(b) Sistan rotor integrated with PAGV on top of the “building”.

The apparatus set-up is shown in Fig. 5. The rotor was in free-running condition where only the inertia and bearing friction were applied. A hand-held laser tachometer was used to measure the rotational speed of the 3-bladed Sistan rotor by pointing it to the rotor shaft.

In order to measure the start-up wind speed of the VAWT, the wind speed was increased gradually until the rotor started to rotate. Then, the wind speed was further increased with several increments and the stabilized rotational speed of the rotor was recorded at each wind speed. These methods were conducted to the both mentioned configurations.

4.2. Wind tunnel testing result and discussion

The rotational speed comparison between the VAWT with and without the PAGV is shown in Fig. 6. An increment of 73.2% in rotational speed was obtained at the wind speed of 3 m/s for the wind turbine with PAGV compared to bare wind turbine. The presence of the PAGV also improved the start-up behavior of the wind turbine. The start-up wind speed of the VAWT with PAGV was 1.5 m/s which is lower compared to the VAWT without the PAGV, i.e. 3 m/s. Longer operating hour can be expected with the lower start-up wind speed as demonstrated by the VAWT with the PAGV.

5. Estimated annual energy savings

The weather data were obtained from the Malaysian Meteorology Department. The data from the weather stations which are in or near to urban areas, i.e. Petaling Jaya (PJ) and Kuala Lumpur International Airport (KLIA) were used for analysis. The data supplied include hourly variation of mean surface wind speed, solar radiation as well as rainfall for the year 2007. The power or energy gained from these parameters can be subsequently predicted.
The wind and solar power generation capacity, and the amount of rain water collected were estimated based on the system geometry as follows:

- Diameter (PAGV) = 30 m, height for inlet (PAGV) = 12 m.
- Diameter (VAWT) = 15 m, height (VAWT) = 6 m.

5.1. Wind energy

The analyzed wind speed data of PJ (year 2007) is used to calculate the wind power extraction of the VAWT. The frequency percentage of total hours and wind energy is plotted as shown in Fig. 7.

Fig. 7 shows that the free-stream wind speed which is less than 4 m/s occurs more than 90% of total hours in year 2007 at PJ. From the analysis of the free-stream wind, the wind speeds in the range of 1.1–1.5 m/s occur with the highest percentage in terms of total hours, i.e. 21.21% but this range just contributes around 3.29% of the energy per year. The highest percentage of wind energy per year with 14.15% contribution is at the wind speed range of 3.0–3.5 m/s.

The wind speed at the surface increases with height rapidly when close to the surface, and the increment rate decreases with the increase in height. The variation of the wind speed with height can be estimated using a power exponent function, given by Eq. (1):

$$ V(z) = V_r \left( \frac{z}{z_r} \right)^\alpha $$

where $z$ is height above the surface, $z_r$ is reference height above the surface, $V(z)$ is wind speed at the height $z$, $V_r$ is wind speed at the reference height $z_r$ above surface and $\alpha$ is an exponent, which depends on the roughness of the terrain and the stability of the atmosphere.

For a typical urban area like PJ, the value of $\alpha = 0.4$ [20], the wind speed at building height of 220 m ($z$) is approximately 1.867 times higher than the wind speed at the reference height (i.e. the height of wind sensor above ground level at PJ weather station) of 46.2 m. Using Eq. (2), the wind power generated after the estimated losses, $P_{\text{wind}}$ can be calculated,

$$ P_{\text{wind}} = \frac{1}{2} C_p \cdot \eta_{\text{TR}} \cdot \eta_{G} \cdot \eta_{\text{PAGV}} \cdot \rho \cdot A_{\text{WT}} \cdot V^3 $$

where $C_p$ is power coefficient. $\eta_{\text{TR}}$ is efficiency due to bearing and transmission loss, $\eta_{G}$ is generator efficiency. $\eta_{\text{PAGV}}$ is efficiency due to power-augmentation-guide-vane (PAGV) loss, $\rho$ is air density (kg/m$^3$), $A_{\text{WT}}$ is swept surface area of wind turbine and $V$ is wind speed.

The wind speed is augmented about 1.8 times after passing through the PAGV and the VAWT also experiences better flow angle (wind stream directionally guided by guide vanes) [21]. With the estimated efficiency of sub-systems or components (Table 1), the wind energy generation could be estimated as shown in Fig. 8. For a system (30 m diameter and 12 m high PAGV, 15 m diameter and 6 m high VAWT) installed on top of a building of 220 m height, the wind energy generated is approximately 58.4 MWh/year or

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**Fig. 5.** Apparatus set-up and three-bladed Sistan rotor of the wind tunnel testing.

**Fig. 6.** Rotational speed comparison between the VAWT with and without the PAGV over wind speed (at wind tunnel testing).

**Fig. 7.** Frequency percentage (total hours and wind energy) versus wind speed at PJ weather station (year 2007).
160 kW h/day. Assuming $C_R$, $η_{VR}$, $η_C$ and $ρ$ are constant; from estimated available wind energy, this system can generate 1.25 times more energy compared to the 30 m diameter and 12 m high VAWT (without PAGV).

5.2. Solar energy

Based on the solar radiation data analyzed at the KLIA weather station located in Sepang, the solar energy generation, $E_{solar}$, is estimated using Eq. (3) [22]:

$$E_{solar} = G_s \cdot A_s \cdot η_{PS} \cdot K$$

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 module conversion efficiency and $K$ is solar power loss. Table 2 lists the value for each coefficient in Eq. (3). Thus, the estimated daily solar energy generated is 280 kW h/day.

5.3. Rainwater

The amount of rainwater collected, $V_{rain}$ (for rain catchment area, $A_c$ of 700 m$^2$), is estimated by using the Rational Equation as in Eq. (4).

$$V_{rain} = A_c \times I \times C_R$$

Table 2 Estimated solar energy generated at KLIA weather station, Sepang (year 2007).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual mean daily global radiation, $G_s$</td>
<td>4.48 kW h m$^{-2}$/day</td>
</tr>
<tr>
<td>Solar panel area above the PAGV</td>
<td>700 m$^2$</td>
</tr>
<tr>
<td>Estimated solar cell active area, $A_s$</td>
<td>650 m$^2$</td>
</tr>
<tr>
<td>Efficiency of solar panel, $η_{PS}$</td>
<td>0.12</td>
</tr>
<tr>
<td>Estimated power loss (electric transmission), $K$</td>
<td>0.8</td>
</tr>
<tr>
<td>Estimated solar energy generated, $E_{solar}$</td>
<td>280 kW h/day</td>
</tr>
</tbody>
</table>

Fig. 8. Estimated wind energy generated on a building (220 m above ground) compared to Petaling Jaya weather station (46.2 m above ground) in year 2007.

Table 3 Summary of estimated annual energy savings.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Energy generated/saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind energy generated</td>
<td>157 kW h/day</td>
</tr>
<tr>
<td>Solar energy generated</td>
<td>280 kW h/day</td>
</tr>
<tr>
<td>Energy saved to pump water</td>
<td>79 kW h/month</td>
</tr>
<tr>
<td>Total estimated annual energy</td>
<td>160 MW h/year</td>
</tr>
</tbody>
</table>

where $I$ is rainfall intensity (mm/month) and $C_R$ is runoff coefficient (assumed as 0.75).

From weather data analysis, the estimated rainwater collected in the PJ area for year 2007 is 132 m$^3$/month. Thus, the energy saved to pump this amount of water (132 m$^3$/month) to the top of a 220 m building is 284.9 MJ/month or equivalent to 79 kW h/month.

The annual total energy generated and saved by this wind–solar hybrid energy generation system and rainwater collector is summarized in Table 3, where the estimated annual energy generated and saved is 160 MW h. According to the annual report published by Tenaga Nasional Berhad (TNB), the average annual electric energy consumption per unit domestic customer or per house in Malaysia (year 2008) is approximately 2.8 MW h [23]. By saving 160 MW h/year, the energy saved is sufficient to supply 57 units of domestic customer yearly.

6. Conclusion

An efficient wind–solar hybrid renewable energy generation system with rainwater collection feature is designed for urban high rise application. The design is a combination that includes wind, solar and rainwater harvesting features, and its technical advantages give rise to the uniqueness of the design. The design can eliminate or minimize the barriers and problems faced by current wind turbines for urban application. It can be integrated into the building without negative visual impact and public concern. The design also eliminates the concern on bird-strike problem, enhances the safety and reduces the vibration. The performance of the PAGV integrated VAWT system is optimized in terms of total operating hour and energy gained by increasing the on-coming wind speed, changing the flow angle for better angle of attack of the wind turbine blades and improving its starting behavior. With these benefits, this system can be a cost-effective construction on the downtown skyscrapers and forms part of tomorrow’s urban landscape.
The wind tunnel testing conducted on the scaled down prototype proved that the PAGV increased the rotational speed of the VAWT (3-bladed Sistan rotor) by 73.2% at the wind speed of 3 m/s. The start-up wind speed of the wind turbine was also improved. With this PAGV integrated wind energy system design, the dimension of wind turbine is expected to be reduced by half, yet generates 25% more energy as compared to the conventional VAWT system without the PAGV. With the 30 m diameter and 12 m high PAGV system, the estimated annual energy savings for Malaysian conditions is 160 MW h. The long-term goal is the proliferation of wind and solar energy applications in populated urban areas, capable of supplying supplementary power to urban buildings.

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