J. Eng. Technol. Sci., Vol. 52, No. 6, 2020, 881-890

Design of True Hybrid Solar Wind Turbine for Smaller Hybrid Renewable Energy Power Plants

Mohammad Al-Ajmi[1], Mohd Khairul Hafiz Muda[2], Izhal Abdul Halin[1], Faizal Mustapha[2] & Mohd Khairol Anuar Mohd Ariffin[3]

[1]Department of Electrical and Electronic Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[2]Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[3]Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
E-mail: hafyz801@gmail.com

Highlights:

- The THWS generator was designed for an output of 24 V.
- The solar capacity of the THWS is 500 W and the wind capacity is 3 kW.
- The total output capacity is 3.5 kW with a footprint of 3.5 m^2.
- An arrangement of THWS generator units in a rectangular grid allows a PPF of only 1.06 acre/MW.

Abstract. Contemporary hybrid solar-wind farms are commonly implemented using separate solar photovoltaic (PV) cell arrays and wind turbines, where the electricity currents generated from both devices are combined. However, this solution requires a large amount of space to cater for the PV arrays and wind turbines of the system. This paper proposes a new type of renewable energy electric generator with a small power production footprint (PPF) that allows reduction of land usage. The True Hybrid Wind-Solar (THWS) generator allows for the solar panels to rotate along with a VAWT wind turbine that is attached through a specially designed electromechanical coupling mechanism. The working principle behind the connections is described in this paper. The design of a hybrid circuit module that serves to combine the currents generated via the solar cells and the wind generator and also to automatically disconnect inactive wind or solar generators is described. The latter is important in order to eliminate unwanted load generated from the inactive generators within the THWS itself.

Keywords: *renewable energy; solar photovoltaics; solar power; solar wind turbine; vertical axis wind turbine; wind power.*

1 Introduction

In the past decade, the world has seen an exponential increase in energy demand. Figure 1 shows the source of actual energy consumption from 1990 to 2015 and

Received July 22nd, 2020, Revised August 4th, 2020, Accepted for publication September 17th, 2020.
 ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2020.52.6.8

its projected path from 2016 to 2040 [1]. This ever-increasing trend is due the growth of the world population.

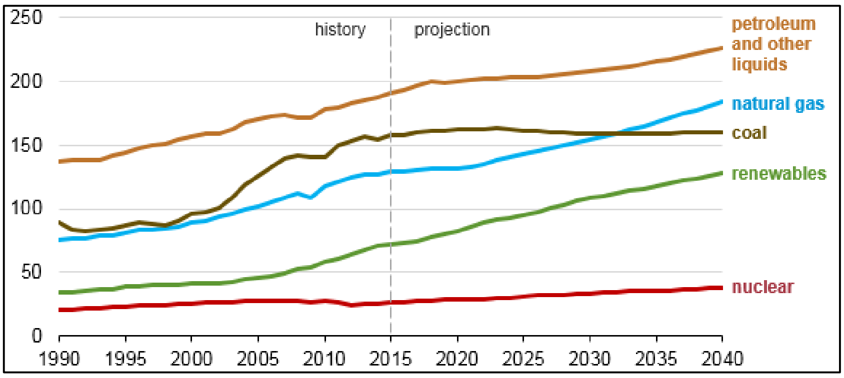

Figure 1 Energy demand [1].

The simple analysis in Figure 1 shows that since 1990 the average energy demand from petroleum, natural gas and coal rose to approximately 50 quadrillion BTU at the end of 2017. Along with this unprecedented increase, the side effect of increased CO_2 emissions has also increased public concern, leading to carbon taxation policies in developing and developed nations [2]. In contrast, it has been observed that from 1990 to 2007 the demand for renewable energy was almost stagnant. However, since 2008 the rate has increased to approximately 2.63 quadrillion BTU/year, which is comparable to the rate of increase in the demand of petroleum and natural gas. This increase in the popularity of renewable energy sources during this period is due to its ability to mitigate CO_2 emission problems as well as advancements in renewable energy technology. For example, a study conducted in Thailand predicts that that the use of solar and wind as a means of electricity generation will result in a decrease of CO_2 emissions by 69.66% in approximately 50 years [3].

The sources of renewable energy available today are solar, wind, biomass, ocean tides, geothermal, hydropower, and others [4]. Although all of these sources are able to produce electricity with zero or negligible CO_2 emission, solar and wind generation methods are the most popular. For example, unlike ocean tide electricity generators, which must be built near the ocean, solar and wind farms can be implemented almost anywhere. Similarly, this is why solar and wind are preferred to geothermal and hydropower generation. However, the area required to produce solar or wind energy is extremely large. This will bring forth socio-economic issues such as lack of land for agriculture and housing.

This paper proposes a new renewable energy-generating device that utilizes both solar and wind energy for the production of electricity in one embodiment. The main objective behind the design was to minimize the area required by using an array of this new type of hybrid generator for large-scale RE power generation.

2 Hybrid Solar Wind Turbine

PV cells produce electricity by means of the photovoltaic effect while wind generators induce electrical current in a coil by cutting a moving magnetic flux through the rotation motion of the propellers of a wind turbine [5,6]. Contemporary hybrid wind-solar farms are designed by connecting a solar farm to a wind farm, making them a clean source of renewable energy [7]. As discussed in the previous section, although energy production is clean, its socio-economic impacts due to the use of large amounts of land for long periods of time is an unwanted side effect of hybrid wind-solar plants.

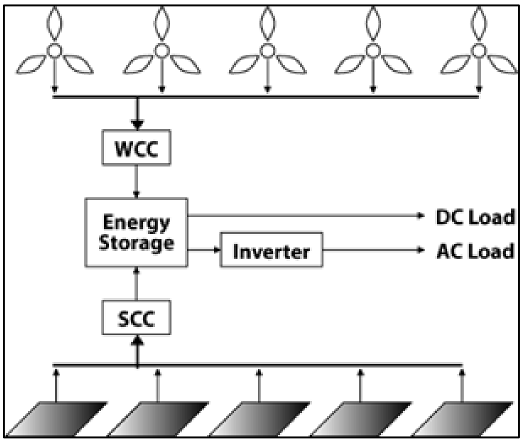

Figure 2 Conventional hybrid wind-solar farm.

A simplified schematic of a conventional hybrid wind-solar farm is shown in Figure 2. When the wind blows, the turbines generate DC current that is fed directly to the wind charge controller (WCC) and when the sun is shining, the solar panels generate DC current, which is fed to the solar charge controller (SCC). Both of the charge controllers charge the system's battery. The battery's DC output is then fed to an inverter that converts it to an AC power signal. The AC signal is fed to a transformer and stepped up according to the specifications of the host grid.

A conventional type hybrid plant uses dedicated solar panels and wind turbines to generate hybrid renewable energy. A hybrid wind-solar generator on the other hand is defined as a renewable energy device capable of generating electricity from wind power and solar irradiation in one embodiment. These devices are a combination of either a horizontal axis wind turbine (HAWT) or a vertical axis wind turbine (VAWT) system coupled with photovoltaic cells. Hybrid wind-solar generators have the combined capacity of its wind energy generating components and solar energy generating components and are placed strategically in areas with high wind density and high solar insolation. Although not yet reported, these new hybrid RE generators are promising devices when it comes to implementing high-capacity hybrid wind-solar farms that use up a small area.

3 Solar, Wind and Hybrid Wind-Solar Farms and Land Area Usage

Along with the rise in world demand for energy from renewable sources, a large amount of information can easily be obtained concerning operators of large-scale solar, wind and hybrid wind-solar energy for the public. These corporations have a public obligation to inform the public on the specifications of their plants. Table 1 shows five operational large-scale solar power plants.

Table 1 Operational large-scale solar power plants.

Reference	Operation Start Year	Location	Number of Panels (million)	Output Capacity (MW)	Area (Hectar^2)
[6]	2016	Kamuthi, India	2.5	648	1000
[7]	2017	Qinghai, China	4	850	300
[8]	2017	Kurnool, India	4	900/1000	2352
[9]	2016	Datong, China	NA	1000/3000	NA
[10]	2016	Ningxia, China	NA	1500	4300

It is clear that the area required to produce MW capacity plants is large. For example, the solar power facility in Kurnool with a targeted capacity of 1 GW requires an area of 2,352 hectares^2. Once a piece of land has been commissioned to build a mega scale solar plant it is rendered unusable for agriculture and settlement for at least a 20-year period, that is the length of the power purchase agreement. This is one of the disadvantages of large-scale solar energy generation.

Table 2 shows five existing mega scale wind farms, their locations and output capacities. These farms are installed with large HAWT, rated around 1 MW of capacity each. Again, it can be seen that the area requirement is extremely high. For example, 12,950 ha^2 of land is required to produce 3 GW from the facility in California. This is mainly to adhere to safety regulations for placement distance between adjacent wind turbines.

Table 2 Operational large-scale wind power plants.

Reference	Operation Start Year	Location	Number of Wind Turbines	Output Capacity (MW)	Area (Hectar^2)
[11]	NA	Gansu, China	7,000	6,000/20,000	NA
[12]	NA	California, USA	750	3,000	12,950
[13]	1986	Tamil Nadu, India	3,000	1,500	NA
[14]	2001	Rajathan, India	NA	1,064	NA
[15]	2012	Oregon, USA	NA	845	20,720

Recently, several hybrid wind-solar power plants have been reported, as shown in Table 3. Information on their respective solar, wind and total output capacity is presented. These hybrid plants have dedicated land to house PV cell arrays and wind turbines to produce electricity. Similar to solar and wind RE plants, the area required to produce hybrid RE power is quite large. However, when compared to pure large-scale solar or wind farms, the usage of land for the generation of hybrid RE power is much more efficient since only 0.16 acres to 2.5 acres of land are required to produce 1 MW.

Table 3 Operational large scale hybrid wind-solar power plants.

Reference	Name/Location	Solar Cap. (MW	Wind Cap. (MW)	Total Cap. (MW)	Area (Acres)
[16]	SECI-NREDCAP/India	120	40	160	1000
[17]	Arena Gullen/Australia	10	165.5	175.5	70
[18]	Fakken Wind Farm/Norway	20	54	74	NA
[19]	Hero Future Energies/India	28.8	50	78.8	NA

The use of large amounts of land for generating green power is seen as a social-economic problem, because once a piece of land is commissioned for a large-scale solar, wind or hybrid wind-solar power plant it cannot be used for agriculture or residential purposes for a period of at least 25 years, based on the period of the power purchase agreement between the RE power producer and the government where the plant is erected. The land requirement for generating RE energy is large due to the dimensions of the devices used to produce electricity. For example, the most efficient and well-designed large-scale solar or wind farms require on average 4 acres of land to generate 1 MW of electricity at full capacity.

4 Proposed True Hybrid Solar Wind Turbine

The proposed True Hybrid Wind-Solar (THWS) electric generator is presented in Figure 3. Labels A, B and C indicate the three different modules of the system, which are called the Solar Blade Module (SBM), the Moving Contact Module

(MCM), and the Hybrid Output Module (HOM), respectively. This particular design is targeted for a total output capacity of 3.5 kW.

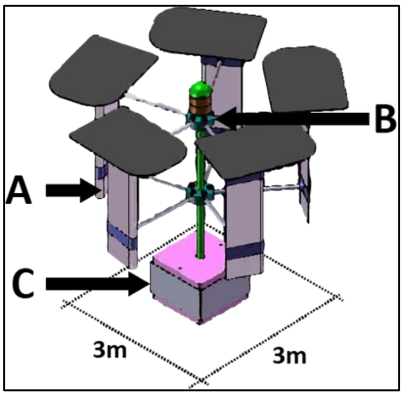

Figure 3 The True Hybrid Wind-Solar electric generator.

Each SBM is a modified Darrieus type blade, where a 100 W PV panel is attached to a plate fitted perpendicular to the Darrieus type blade. Since there are five SBMs, the expected capacity is 500 W. The size of the blade and the dimensions of the THWS generator are determined by the dimensions of the PV cells used. In general, a PV of 1 m x 0.5 m has a capacity of 100 W, thus the THWS generator's footprint is 3 m x 3 m.

Since all of the SBMs rotate, the problem of extracting the power signal produced by the PV cells is anticipated. The MCM was designed to tackle this problem. Figure 4 shows a schematic of the simplified circuit of the TWHS generator. The MCM comprises two fixed rings. The top fixed ring maintains the connection of the PV cell's positive terminal to the PV cell output port of the THWS generator, while the bottom ring does the same for the negative terminal. The contacts of each respective PV output terminal orbit its respective fixed rings as the SBM rotates in the wind. At the PV output terminal, electricity is tapped directly from the fixed ring with a voltage of 24 V.

The HOM on the other hand serves two purposes. The first is to generate electrical energy from the wind via the generator, as shown in Figure 4. It is important to use a DC output generator for ease of combining solar and wind energy as the end product. A 3-kW capacity output is expected from the VAWT with a footprint of 3 m x 3 m footprint in this design.

The HOM's second purpose is to electrically isolate non-generating RE generators within the THWS generator. For example, on a windy night, the PV cells are dormant, so the HOM will electrically isolate all of the SBMs from the system. This also serves to prevent loading from the PV cell's junction capacitance onto the system. Figure 5 shows the circuit contained in the HOM responsible for this task.

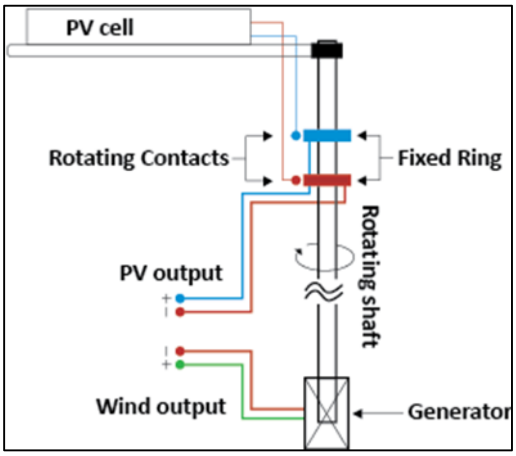

Figure 4 Schematic of the true hybrid wind-solar modules.

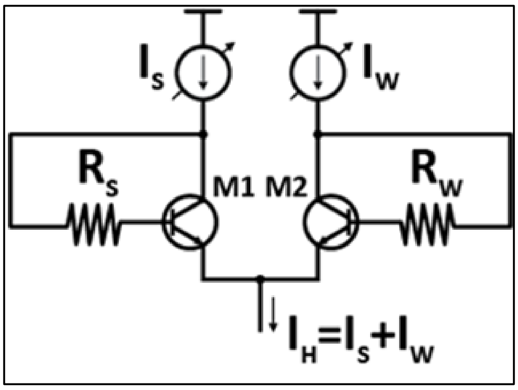

Figure 5 Hybrid power selection module.

Two power transistors (M1 and M2) capable of carrying currents of 5 A are used. I_S and I_W denote the solar and wind currents, respectively. As base resistances, RS and RB are connected to M1 and M2 in order to induce a voltage drop when I_S and/or I_W are/is present. The generated voltage across these resistances will turn on each respective transistor. When no voltage is induced, the transistor will turn off. In case the PV cells are not producing electricity, M1 turns off and $I_H = I_W$. When no wind is present, M2 turns off and $I_H = I_S$. However, when both the PV cells and the wind generator are producing current, both transistors are turned on, so $I_H = I_S + I_W$.

5 Estimation of THWS Electric Generator Power Production Footprint

The power production footprint (PPF) is defined for the first time in this work. The PPF is the area required by a power plant to produce 1 MW of electricity. PPF can be used to measure the land-usage efficiency of RE plants for monitoring their socio-economic effect or simply as data for the planning of large-scale RE plants. In this paper, it is used to compare between the efficiency of land usage of a plant composed of THWS generators and a power plant composed of PV cell arrays or wind turbine generators.

Figure 6 is a depiction of the layout of several THWS generators arranged in a rectangular grid for the implementation of a large-scale power plant. The raw footprint of one THWS is 3 m x 3 m. To allow for safety and as a path for service and maintenance it is suggested that the distance between two raw footprints should be 1 m. This results in a footprint of 3.5 m^2 between two adjacent THWS generator units. Since the capacity of one THWS generator is designed to be 3.5 kW, 290 units are required to produce 1 MW. With a footprint of 3.5 m^2 each, the total area required using the arrangement in Figure 6 is 3552.5 m^2, equivalent to 0.88 acres of land. If 20% more allowance is considered for other plant facilities such as transformers and inverters, the PPF of the THWS generator is approximately 1.06 acres/MW.

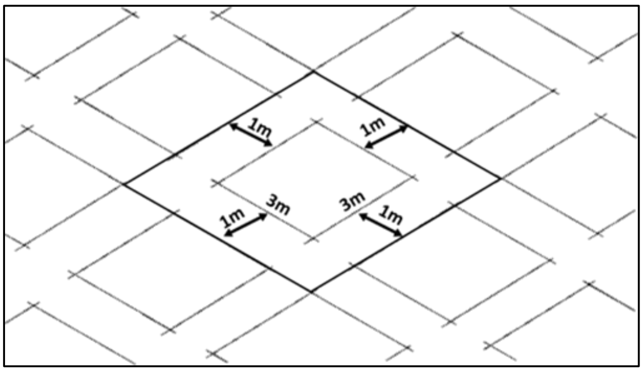

Figure 6 THWS generator layout for large-scale power plants.

6 Conclusion

The analysis of area usage between large-scale hybrid wind-solar power plants and their counterparts, either large-scale pure solar or wind plants, showed that hybrid RE plants have a much smaller PPF, making them much more area efficient. For example, the hybrid facility in Australia has a PPF of only 0.16 acres/MW. However, these RE power plants use a traditional hybrid wind-solar topology in which dedicated PV cell arrays and wind turbines are used separately to produce hybrid renewable energy. Nonetheless, it is noted that hybrid type farms are more area efficient and in the long term will lower negative socio-economic impacts such as shortages of land for agriculture and housing.

Figure 7 THWS generator power plant land size comparison.

The recent emergence of hybrid wind-solar RE generators in the market has opened the opportunity for the development of large-scale true hybrid wind-solar plants. However, in the existing models either the generation capacity is too low or the PPF is too high. Therefore, the THWS electric generator was proposed in this paper. It was designed with a moving contact module that in the not so distant future will allow the blades of a wind turbine generator to be fabricated from PV material. In this work, placement of the PV cells in the proposed configuration not only allows a small PPF but also introduces a cooling effect to the PV panels, which in turn boosts the efficiency of the cells. The hybrid output is tapped from the THWS generator via a dedicated HOM circuit. The THWS electric generator is designed for an output of 24 V with a solar capacity of 500 W and a wind capacity of 3 kW, giving a total output capacity of 3.5 kW with a footprint of 3.5 m^2. The arrangement of the THWS generator units in a rectangular grid will allow a PPF of only 1.06 acre/MW. As depicted in Figure 7, the PPF of a large-scale THWS plant is approximately a quarter of the PPF of a conventional large-scale solar or wind farm.

Nomenclature

HOM	=	Hybrid Output Module
MCM	=	Moving Contact Module
PPF	=	Power Production Footprint
PV	=	Photovoltaic
SBM	=	Solar Blade Module
THWS	=	True Hybrid Wind-Solar

References

[1] British Petroleum, *BP Statistical Review of World Energy. London: Workbook (xlsx)*, 2016.

[2] Richard, S., Thomas, M.S. & Ruth, A.J., *World Carbon Dioxide Emissions: 1950-2050*, Review of Economics and Statistics, **80**(1), pp. 15-27, 2006.

[3] Tri, V.K., Usumadewi, Pornphimol, W. & Bundit, L., *Long-term CO_2 Emission Reduction from Renewable Energy in Power Sector: The Case of Thailand in 2050*, Energy Procedia, **138**, pp. 961-966, 2017.

[4] Antonia, V.H., Timothy, E.L., Jennifer, L.E. & Daniel, M.K., *Renewable Energy: A Viable Choice*, Environment, **3**(10), pp. 8-20, 2001.

[5] Boyle, G. *Renewable Energy: Power for a Sustainable Future,* Oxford University Press, 2004.

[6] Hau, E., *Wind Turbines, Fundamentals, Technologies, Applications and Economics*, 2nd Ed. Berlin: Springer, 2006.

[7] Yashwant, S., Gupta, S.C., Bohre, A.K. & Meng, W., *PV-Wind Hybrid System: A Review with Case Study*, Cogent Engineering, **3**(1), pp. 1-31, 2016.

[8] Pierrick, I., *Design and Test of a 3D-printed Horizontal Axis Wind Turbine*, Université Catholic de Louvain, Master Thesis Dissertation, pp. 53-54, 2016.

[9] Hashim, H. & Ho, W.S., *Renewable Energy Policies and Initiatives for a Sustainable Energy Future in Malaysia*, Renewable and Sustainable Energy Reviews, **15**(9), pp. 4780-4787, 2011.

[10] Herbert, G.J., Iniyan, S., Sreevalsan, E. & Rajapandian. S., *A Review of Wind Energy Technologies*, Renewable and Sustainable Energy Reviews, **11**(6), pp. 1117-1145, 2007.

[11] Leung, D.Y. & Yang, Y., *Wind Energy Development and its Environmental Impact: A Review*, Renewable and Sustainable Energy Reviews, **16**(1), pp. 1031-1039, 2012.

[12] Saeidi, D., Sedaghat, A., Alamdari, P. & Alemrajabi, A.A., *Aerodynamic Design and Economical Evaluation of Site Specific Small Vertical Axis Wind Turbines*, Applied Energy, **101**, pp. 765-775, 2013.