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ORIGINAL ARTICLE

A Detailed Review on Wind and Solar Hybrid Green Energy Technologies for Sustainable Smart Cities

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Abstract
Smart City development is a program for urban redevelopment and refurbishment. The main goal of a smart city is to stimulate economic growth and improve the quality of life of people by facilitating local area development and utilizing technology, particularly technology that leads to Smart results. Power generation is also a very crucial factor in the power management of smart cities. Most developing countries still use non-renewable energy sources as their conventional ones for power generation. The important problems arising from Non-Renewable energy sources are the depletion of natural resources, incremental greenhouse gases, pollution of the environment, and the rising cost of power consumption. Nowadays, the people and government are becoming more conscious of the significance of switching from conventional energy sources to renewable energy sources as we become more mindful of our impact on the environment. Green Energy or Renewable Energy is a way to make our Smart cities and Power Grid more sustainable. Hydroelectric, Solar, Tidal, Wind, and Bio-gas are a few of the important green energy sources used for power generation. Solar and wind power harvesting can be adopted and more suited for the Smart city-like urban environment. Since solar radiation and wind speed change throughout the year, neither a solar nor a wind-powered system can offer consistent electricity individually. By considering this condition, hybrid solar and wind power harvesting is suggested for sustainable Smart future cities. The present work explains solar power, wind power, and hybrid solar-wind power harvesting in detail with a Smart City power generation perspective.

Keywords Smart cities · Wind power · Solar power · Hybrid solar-wind power · Green energy · Renewable energy · Power generation

1 Introduction

Green energy technologies allow us to use renewable energy sources to generate heat, fuel, and electricity. The sun powers solar, hydro, wind, heat exchange, wave, tidal, and bio-energy technologies, either explicitly or implicitly (Gibson et al. 2017). Deep heat from the Earth's core powers geothermal technologies (Anderson and Rezaie 2019). The moon is used to power wave and tidal energy technologies (Webb 1982). The energy can be converted which is stored in plants, farm and food wastes, forest wastes, algae, and sewage into fuel, heat, and power using bio-energy technologies (Fiorese et al. 2014). These technologies enable us to generate electrical power and heat/cool our buildings while avoiding the release of harmful greenhouse gases and other pollutants (Amponsah et al. 2014). In Green energy technologies, solar power harvesting and wind power harvesting are more dominant due to their presence and abundant nature (Benson and Magee 2014).

A smart city is an urban area that gathers information via the use of numerous sensors and technological devices. The information acquired from the data is used to manage resources, services, and assets efficiently; The information is then used to improve city operations. In order to monitor power plants, energy management, transportation, utilities, information systems, schools, hospitals, and other community services, data from buildings, devices, and residents is gathered, processed, and evaluated (Camero and Alba 2019). Figure 1shows the various sectors to be considered in the Smart city like the urban environment. For the sustainable future of smart cities, power generation and its management will be the important criteria. In addition, pollution reduction, saving natural resources, efficient management

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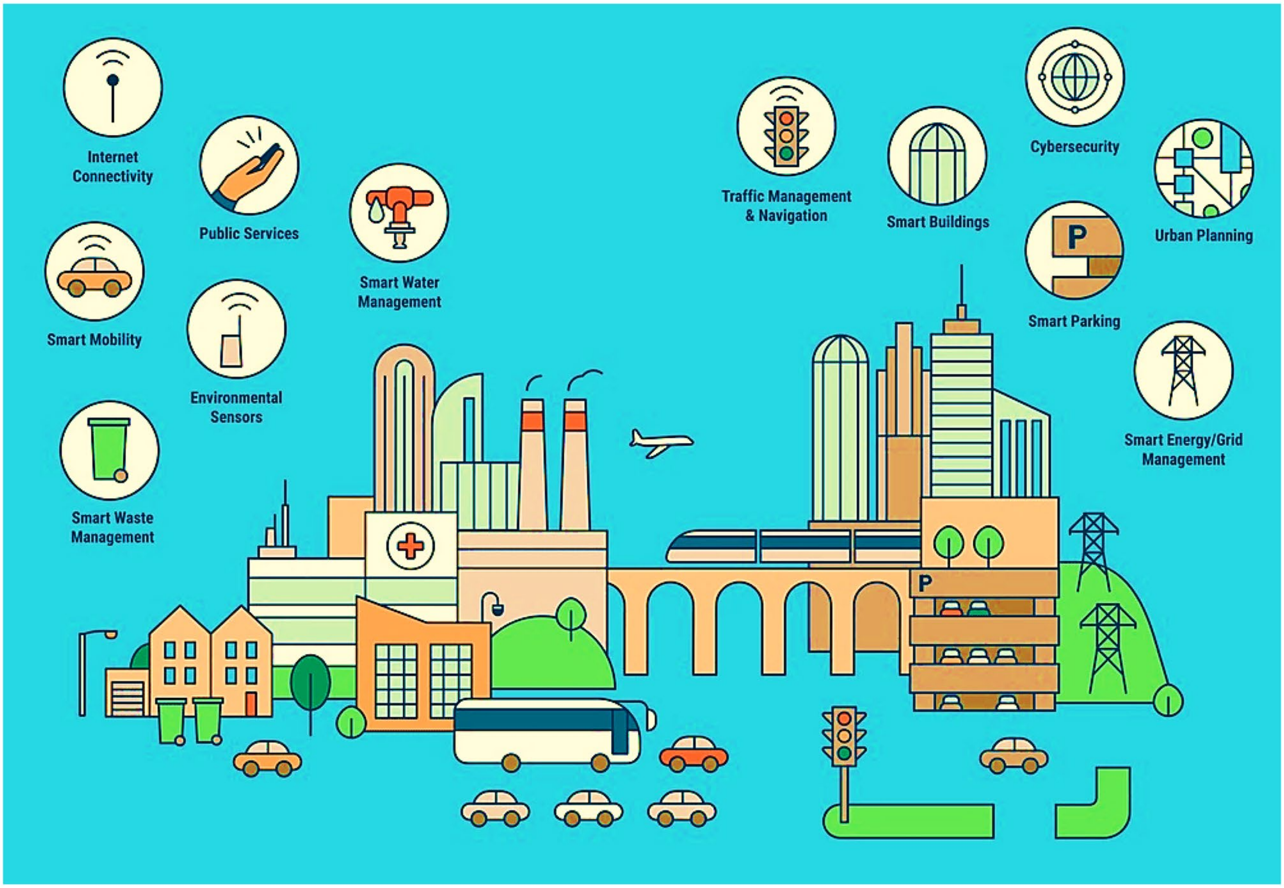


Fig. 1 Smart City

of the resource, and good space management are considered important aspects of smart cities (Raj et al. 2022).

All these aspects of Smart cities are considered, and power generation through green energy technologies is highly recommended (Mahmood et al. 2021). Because conventional methodologies like non-renewable energy-based power generation create lot more problems for the environment, it is also causing the depletion of natural resources, and the cost of production of energy is also becoming higher. But these non-renewable resources have another source of the problem. All these sources are not available in a single place, and it is not constant throughout the year (Azarpour et al. 2013). Compare with any other renewable energy sources, this wind and solar are abundant in nature and available irrespective of location (Panwar et al. 2011). Merging these two green energy technologies forms a hybrid solar-wind power harvesting methodology. It will be very useful in pollution-free, eco-friendly, and cost-effective power generation in Smart cities. In this prelude, the present work explores the detailed study of solar energy systems, wind energy systems, and hybrid solar-wind energy systems suited for smart cities like urban setups. The experimental and simulation study is also carried out to prove the efficiency of the hybrid system which is suited for sustainable smart cities.

2 Literature Review

The Smart Cities Mission's purpose is to promote cities that offer a high quality of life to their citizens, as well as basic infrastructure, a sustainable and clean environment, and the usage of "Smart" solutions. Power generation using green energy technologies is also another crucial factor that needs to be considered at the time of smart city planning. There are numerous works reported in the literature regarding the smart city. A few of the notable works are tabulated in Table 1.

There are similar works reported in the literature. Solar and wind are the most important green energy technologies. Solar energy is harvested using PV cells, and wind turbines harvest wind energy. Solar energy harvesting is lacking in certain areas, such as space constraints (Albert et al. 2022). In a similar manner, Wind energy harvesting also has certain shortfalls. The wind speed does not remain constant, it varies

Table 1 Notable Works in the Literature

Author	The focus of the Study	Inferences
Bakıcı et al. (2013)	Utilizing Information and Communication Technologies (ICT) to transform the cities, urban growth and policymaking of smart cities.	A unique model of the smart city is proposed. The benefits and challenges of adopting ICT are also explained. In addition, the importance of renewable energy-based power generation is also insisted.
Hall et al. (2000)	Explained the importance of each smart city's vision and mission statements	According to the authors, these statements need to focus on electrical power generation and management, water management and treatment, and transportation as their major focus.
Yigitcanlar et al. (2021)	Briefed on how smart city concepts and technologies are perceived and utilized.	Provided various guidelines in power management and came out with an example of the smart city mission in Australia.
Qi and Shen (2019) and Bonetto and Rossi (2017)	Presented different energy management techniques for future smart cities	Power generation and its proper utilization play a vital role in sustainable smart cities. The importance of incorporating green energy technologies is emphasized.
Singh et al. (2019)	Explained Solar power harvesting using Photovoltaic (PV) cells for the intended smart city of Pondicherry in India	Feasibility analysis of grid-tied solar power plants and electric mobility facilities proved the effectiveness of green energy technologies.
Northfield (2016)	Discussed the importance of solar power harvesting for greening the smart city.	Provided a detailed architecture for exposing the damning evidence of energy and environmental dangers using Big Data.
Klonari et al. (2016), Samal et al. (2018) & Hoang and Nguyen (2021)	Explained the opportunities and advantages of solar power harvesting in smart cities like urban environments	Photovoltaic (PV) cell array installation is somewhat easier than other sets of green energy sources. But the solar power generation has some drawbacks compared with other green energy sources. The maximum output obtained from the PV cell is minimum compared to other sources.
Wang and Hsu (2011), & Zhou et al. (2021)	Explained the placement of solar cells in a smart city environment and analysed the issues related to power generation	Solar radiation is also getting varied throughout the year. Because of this also the power generation using PV arrays is not constant. Due to these issues, the power conditioners will have more stress in stand-alone PV systems. For the small amount of power generation also, it needs more amount of space requirement.
Li and Chen (2008) & Appadurai et al. (2022)	Wind energy harvesting using wind power generators is discussed	The work proved that wind power generation is more efficient than solar power harvesting. But the space requirement is the biggest concern in wind power generation.
Appadurai and Raj (2022) & Gupta and Srivastava (2018)	Presented the small-scale wind turbines can be placed on the rooftop and suited for urban applications.	The nanocomposite-based wind blades are proposed and utilized for making small-scale wind turbines. They are less in weight and suited for an urban environment.
Dhunny et al. (2016)	Wind power generation in Mauritius	Different types of wind turbines used for power generation are reviewed. Explored the capabilities of a vertical axis wind turbine in power generation.
Tascikaraoglu (2018)	Evaluation of Spatio-temporal forecasting methods in various smart city applications	Discussed the assessment of different forecasting methods for various smart city-based wind power generation applications.
Singla et al. (2020)	Development of an Efficient, Cheap, and Flexible IoT-Based Wind Turbine Emulator	Proposed the Internet of Things (IoT) based wind turbine emulator for a smart city like the urban environment, and it is more efficient, cheap, and flexible.
Wang et al. (2016)	Efficient scavenging of solar and wind energies in a smart city	The efficient implementation and integration of solar and wind power technologies in the smart city-like environment.
Karthick et al. (2021)	Optimization of PV-Wind Hybrid Renewable Energy System for Health Care Buildings in Smart City	Optimizing the PV-wind energy system for healthcare buildings in smart cities is explained.
Alagar et al. (2021)	Standalone PV-Wind-DG-Battery Hybrid Energy System for Zero Energy Buildings in Smart City Coimbatore, India.	Proposed PV-wind hybrid systems and Diesel generator-battery systems for smart city power generation in Coimbatore, India.

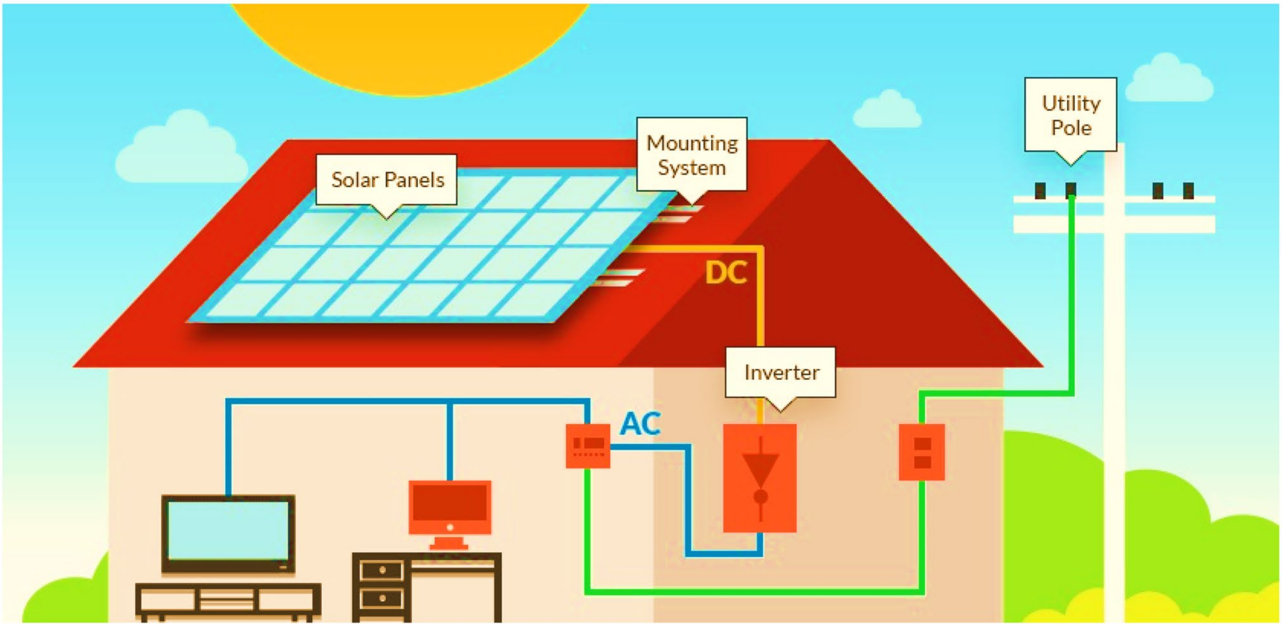


Fig. 2 Solar Panel Installation on the Rooftop

seasonally. Therefore constant power generation throughout the year will be another constraint (Nayagam et al. 2022).

Solar and wind power harvesting has some drawbacks when it operates individually in a smart city-like urban environment. Therefore, hybrid solar-wind power harvesting is proposed to ensure constant power generation. In this context, the present work adopts hybrid wind and solar technology to extract energy from renewable sources and is most suited for a smart city-like urban environment.

3 Solar Power Harvesting in Smart cities

Solar applications that use solar energy, such as solar street lighting, solar water heaters, and rooftop solar, can go a long way toward making smart cities a cleaner and greener place to live. Green energy (Solar) has the potential to play a major role in the development of smart cities. It is a renewable energy source since it can generate electricity as long as the Sun illuminates. It is more eco-friendly. It is a reliable, clean, non-polluting energy source that can be used instead of fossil fuels. It produces no hazardous gases like Sulphur oxide, carbon monoxide, nitrogen oxide, or carbon dioxide. As a result, the risk of environmental damage is lowered. Because solar energy is generated by the Sun, it does not necessitate the transportation of fuel or radioactive waste storage.

3.1 Solar Panel / Photovoltaic (PV) Panel

Solar panels (PV panels) can be used to harness the sun's solar energy, which is a never-ending source of energy. It helped us become less reliant on nonrenewable energy sources. Thus, it will help to maintain a clean and green environment. Solar panels can be mounted almost anywhere. Solar panels are typically installed on rooftops, so they do not require any additional space. Figure 2 shows the simple installation of PV panels in a single house. Solar panels are expensive to install, but once they are, the advantages can be enjoyed for years with little maintenance. Panels can constantly be added as needed, and this does not require much money. These panels make no noise and do not emit any toxic substances. It also helps you to save money on your power bills. The cost of electricity is reduced by installing solar panels in homes. Solar energy can be used for several purposes, including lighting arrangement, automobile charging, water heating, and home heating. It has the potential to reduce energy expenses by up to 30% (Pushparaj et al. 2022).

Rooftop installation costs vary significantly depend on the roof type and its various substructure, the solar panel design, and the area's typical wind and snow conditions. Roof mounting is, in general, more difficult than ground or pole mounting. On the other hand, residential installations are more likely to be roof mountings because the roof is the largest and most open location on the building. Roof mount panels are fixed mounts, meaning they do not move with the Sun. The mounting system also referred to as the racking system, can do more than simply keep your solar panels in place at a 30 to 45 degree angle (Abu-Rayash and Dincer 2021; Appadurai et al. 2022). The mounting determines the orientation of the solar modules with respect to the Sun. The panels that were more properly positioned generated more power. Figure 3 shows the mounting arrangement of the PV panels on the rooftop.

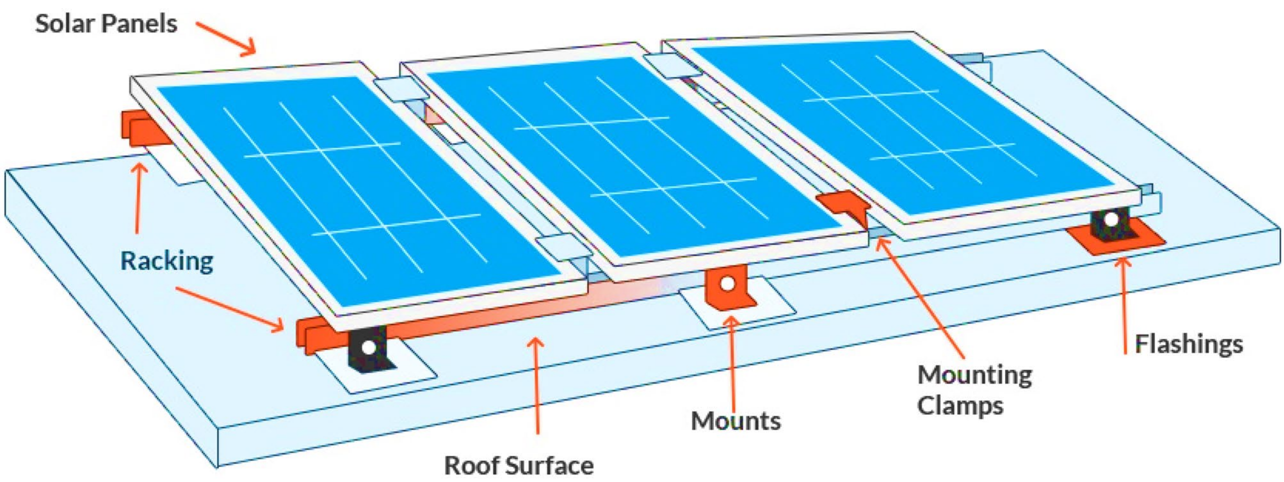
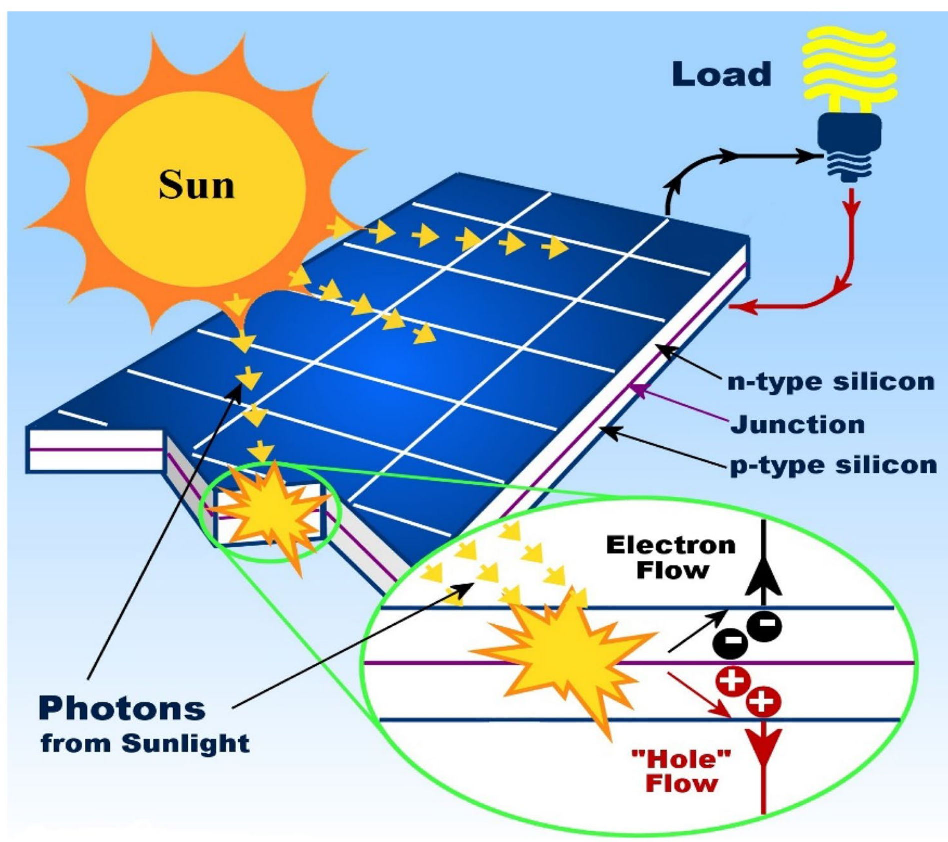


Fig. 3 Rooftop Mounting Arrangement of the PV Panel

3.2 Solar Cell / PV Cell

A photovoltaic (PV) cell, commonly known as a solar cell, is an electronic component that creates electricity when exposed to photons or light particles. It is made of semiconducting materials; The term "semiconductor" implies a material's capacity to conduct electricity more efficiently than an insulator but not as efficiently as a good conductor. When light strikes a PV cell, the solar energy is absorbed and transferred to negatively charged electrons within the material. An electrical current is created when this increased energy permits electrons to move through a material. This current is then absorbed and used to energize our home and the rest of the electric grid via conductive metal connections in the PV panel (grid-like lines on PV cells).

Fig. 4 Photovoltaic Cell



P and n semiconductors are the building blocks of a photovoltaic cell, and solar radiation absorption causes the p-n junction to create pairs of electron holes. When a pair is formed far from the p-n junction, it swiftly recombines (Gray 2003). The internal electric field divides the holes and electrons during solar radiation absorption in or around the p-n junction. Following that, the holes move to the p side and the electrons to the n side. The movement of holes and electrons creates a potential difference or voltage at the solar cell's ends (Fig. 4).

When the contact potential is applied to the p–n junction, the holes travel up the inclination of the valence band and the electrons go down the inclination of the conductive band resulting in a decrease in the contact potential difference of the p–n junction. A new equilibrium state for the p-n junction can be attained by changing the open-circuit potential difference, which is influenced by the strength of the incident solar radiation. The electrical circuit will generate a direct current if the PV cell is connected to an external load.

The ratio between the electrical power generated by the solar cell to the energy emitted when the light strikes the solar cell is defined as the efficiency of a PV cell. This ratio indicates the efficiency of the PV cell at converting light energy into useful electrical energy. PV cells generate electricity based on the characteristics of the available light (such as wavelengths and intensity) and the solar cell's numerous quality attributes (Singh and Ravindra 2012). The bandgap of a photovoltaic semiconductor is critical because it determines the wavelengths of light it can absorb and convert to useful electrical power. The solar cell can efficiently use all of the available power when the semiconductor bandgap matches the wavelengths of light that reach it.

3.3 Commonly used PV cells

3.3.1 Silicon PV cells

Silicon is the world's second most prevalent element (after oxygen) and the most common semiconductor in computer chips. It's also the most common semiconductor material in photovoltaic cells, accounting for over 95% of all modules made and distributed (Yoo et al. 2021). To make crystalline silicon cells, silicon atoms are connected in a crystal lattice (Combari et al. 2021). This arrangement provides a well-organized structure that maximizes light-to-electricity conversion. As a result, silicon PV cells now provide a fair mix of lifetime, cost, and efficiency. These Silicon PV modules will endure at least 25 years and produce more than 82 per cent of their original power (Zheng et al. 2022; Sijini et al. 2016).

3.3.2 Quantum Dots PV Cells

Quantum dots, small fragments of different semiconductor materials that are only a few nanometers across, are used in quantum dot solar cells to generate power. This methodology offers a novel method of processing semiconductor materials, but they are currently inefficient because it is difficult to connect them electrically. They are, however, easily converted into photovoltaic cells (Ghosh et al. 2021). They can be applied to a substrate using a spray, roll-to-roll printers, and a spin-coat method similar to those used for newspaper printing. These types of PV cells come in various sizes. They feature a variable bandgap, allowing them to absorb difficult-to-capture light and combine them with many other semiconductors, like perovskites, to improve multijunction PV cell performance.

3.3.3 Organic PV (OPV)

Organic PV cells are made up of carbon-rich (organic) molecules that can be tweaked to improve certain photovoltaic functions like colour, transparency, or bandgap (Burlingame et al. 2020). While OPV cells are presently less effective and have shorter working lifetimes than crystalline silicon cells, they are much less expensive to produce in large quantities. OPV may be applied in a wide variety of supporting materials, including flexible plastic, enabling it to be used in various applications.

3.3.4 Perovskite PV

Perovskite PV cells are a form of thin-film PV cell distinguished by their unique crystal structure. Printing, or coating, or vacuum deposition is used to deposit materials into an underneath basic layer, referred to as the substrate, in these types of cells. They are usually simple to assemble and offer efficiency levels that rival crystalline silicon (Khan et al. 2020). PV cell efficiencies have increased at a quicker rate than any other PV material in the lab, rising from 5% in 2010 to over 25% by 2020 (Wang et al. 2021). These photovoltaic cells must become robust enough to last 20 years in the outdoor environment before becoming economically feasible, which is why researchers are aiming to increase their endurance and develop low-cost production procedures on a wide scale (Ghadikolaei 2021).

3.3.5 Thin-Film PV

One or more thin layers of photovoltaic material are deposited on a substrate such as metal, plastic, or glass to make a Thin-Film solar cell. Copper Indium Gallium diselenide (CIGS) and cadmium telluride (CdTe) are the two main types of thin-film photovoltaic semiconductors accessible today. Both materials could be directly deposited on the rear or front surfaces of the module. While CIGS cells in the lab show ideal photovoltaic characteristics and excellent efficiencies, the intricacy of mixing four different elements renders the transition from the lab to production more complicated and challenging (Regmi et al. 2020). After silicon, CdTe is the

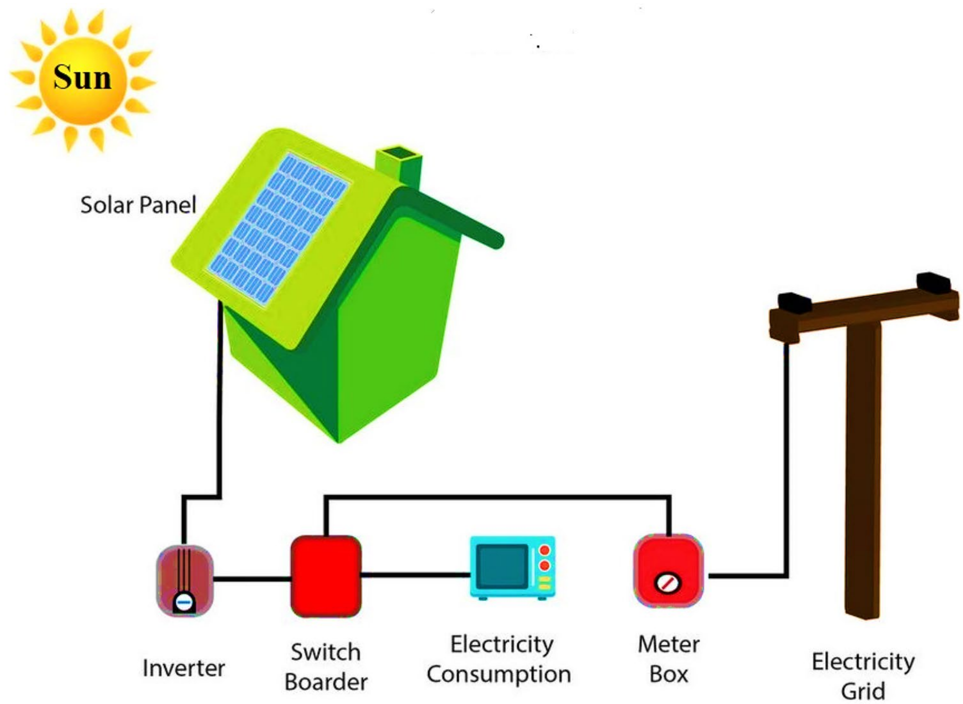


Fig. 5 On-Grid Solar System

next most commonly used photovoltaic material, and CdTe cells may be made utilizing low-cost production procedures. While this offers them a less expensive option than silicon, their efficiency is still not as good. Furthermore, to operate outdoors for an extended length of time, CIGS and CdTe require more shielding than silicon (Weiss 2021).

3.4 Types of Solar Power Systems

3.4.1 On-Grid Solar System

The grid-tie or on-grid system is by far the most prevalent and widely used type of solar system. These systems use conventional

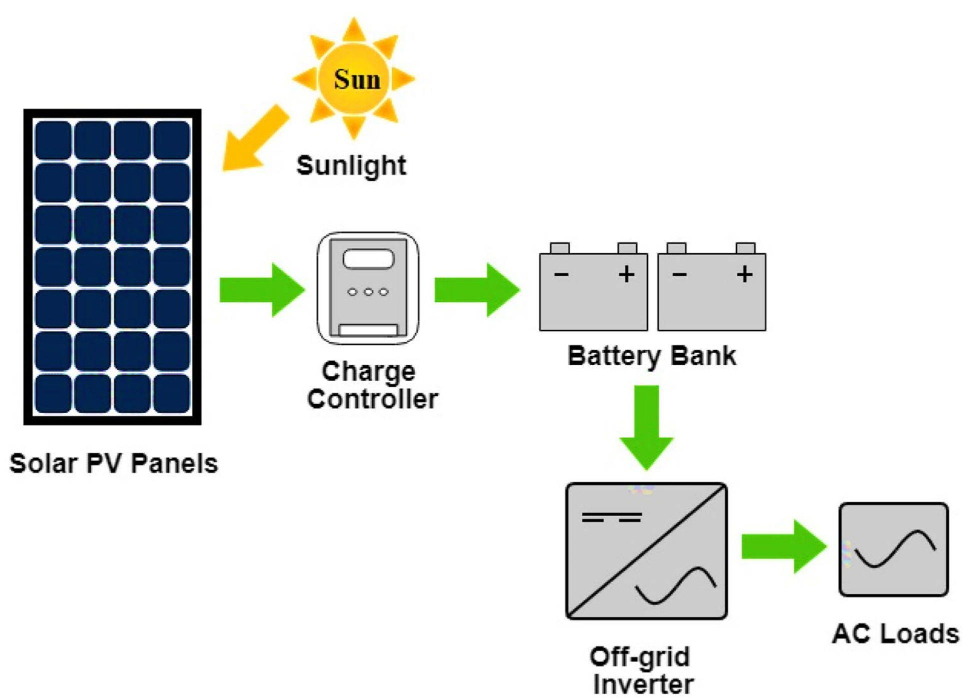


Fig. 6 Off-Grid Solar System

solar inverters to connect to the public electrical grid and do not require batteries. Two ways of power transfer are possible in this network. Any surplus solar energy generated is normally exported to the grid, and you are rewarded for the energy exported through a feed-in tariff or credits. On-grid solar systems are unable to operate or generate electricity during a blackout due to safety concerns (Khandelwal and Nema 2021). Because blackouts often occur when the electrical grid is damaged, continuing to feed electricity into a damaged grid would endanger the safety of people working to repair the faults. Figure 5 shows the On-Grid Solar power system.

3.4.2 Off-Grid Solar System

An off-grid system requires battery storage because it is not connected to the power grid. This type of solar system must be appropriately constructed to generate enough electricity throughout the year and have the sufficient battery capacity to satisfy the home's needs, even during the darkest months of the year when sunshine is limited. Off-grid systems are substantially more expensive than on-grid systems due to the high cost of batteries (Zhang et al. 2021). Therefore, they are typically required only in distant places that are not connected to the

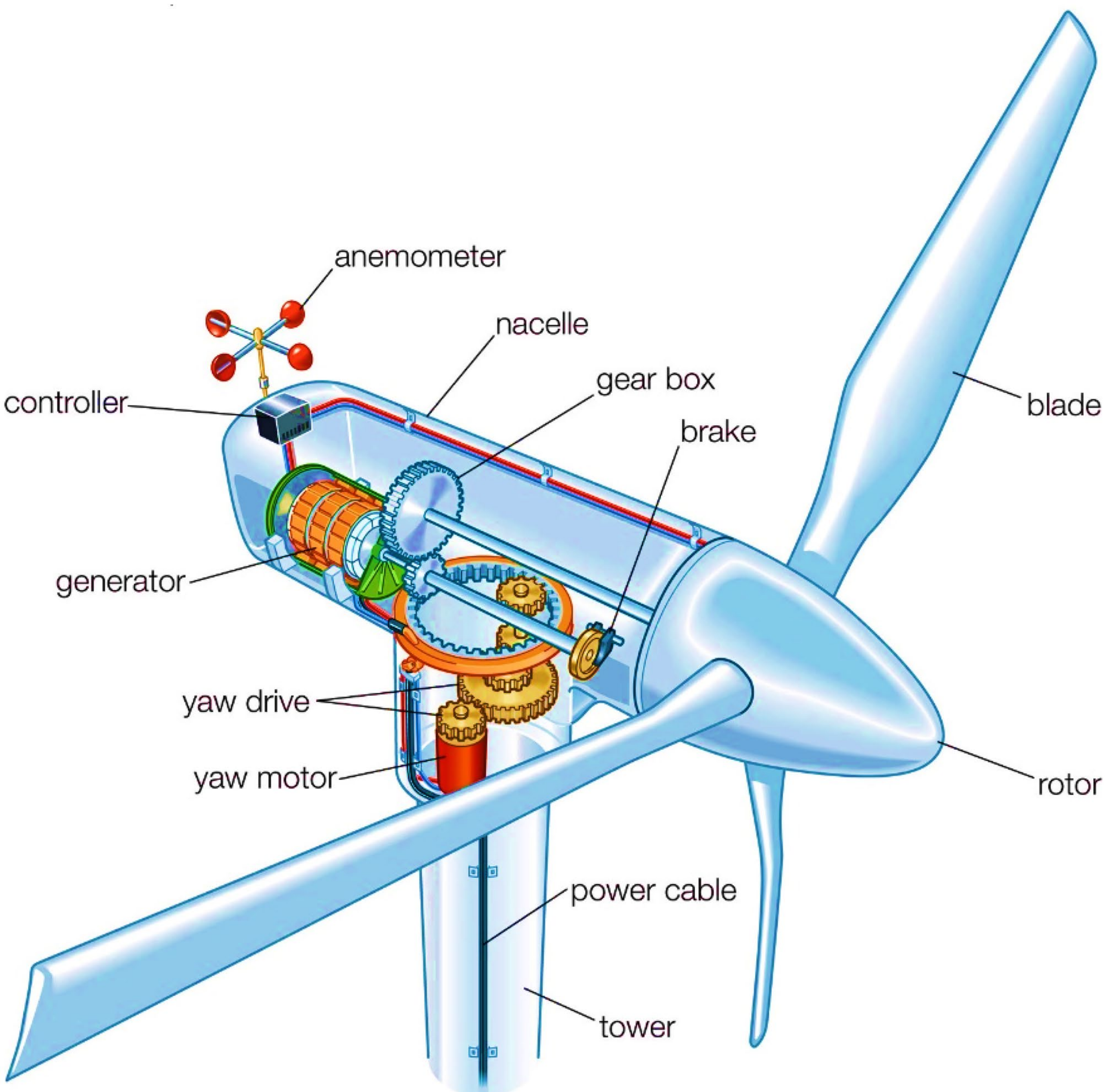


Fig. 7 Wind Turbine (Source 2022)

power grid. As battery prices come down, a new market for off-grid solar battery systems is emerging, even now, in towns and cities. Figure 6 shows the Off-Grid Solar power system.

4 Wind Power Harvesting in Smart Cities

Wind power can be harvested using wind turbines combined with a wind generator. These devices convert wind energy into useful electrical energy. Normally wind turbines can be placed near the on-shores or off-shores. It can also be placed in the urban environment, like smart cities for power generation. It is one of the important green energy technologies which aid the environment in terms of less pollution (Rose and Benifa 2021). The placing of wind turbines in smart cities is the main problem behind wind energy harvesting. When it is placed over the buildings, sometimes it creates sound and vibration. Even though reduction of sound and vibration can be made by using specialized techniques.

4.1 Wind Turbine

As we mentioned earlier wind turbines combined with wind generator converts the wind's kinetic energy into useful electrical energy. The rotor blades, which function similarly to an aeroplane wing or a helicopter rotor blade, are used to generate aerodynamic force. When the wind blows across the blade, air pressure on one side of the blade decreases. The difference in air pressure between the blade's two sides produces the drag and lift forces. The rotor begins to rotate whenever the Lift force exceeds the Drag force (Amjith and Bavanish 2021; Appadurai and Raj 2021). The rotor will be either directly connected to the generator or via a shaft as well as a series of gears in the gearbox, which accelerates the rotation speed in rated values and enables the generator to be physically small in size. Thus the power is generated by converting aerodynamic force to rotation of the generator. The several important components of the wind turbine are depicted in Fig. 7.

The wind speed is measured by an anemometer, which delivers the data to the controller. Turbines with three or two blades are the most common. The controller initiates the turbines and shuts them down at 55 mph at wind speeds of 8 to 16 mph (approximately). Turbines are not designed to function in winds over 55 mph because the high winds can cause damage to them (Hahn et al. 2007). The rotor of a wind turbine is stopped manually and electronically using brakes. By connecting the low-speed and high-speed shafts, the gearbox raises rotational speeds from 30 to 60 revolutions per minute (rpm) to 1000–1800 rpm, which is the rotational speed needed by the majority of generators to produce energy (Raj and Kamraj 2013). A wind turbine's gearbox, on the other hand, is an expensive (and heavy) component; As a result, engineers are considering "direct-drive" generators, which operate at lower rotational speeds and do not require gearboxes. The Wind generator generates 50 Hz AC electrical energy. There are numerous types of wind generators used in the present world. Squirrel Cage Induction generators, Doubly fed Induction Generators, Synchronous generators, and Switched Reluctance generators are a few of the important generators used in the present world (Raj and Balaji 2021).

Fig. 8 HWT placed over the Rooftop (Pellegrini et al. 2021)

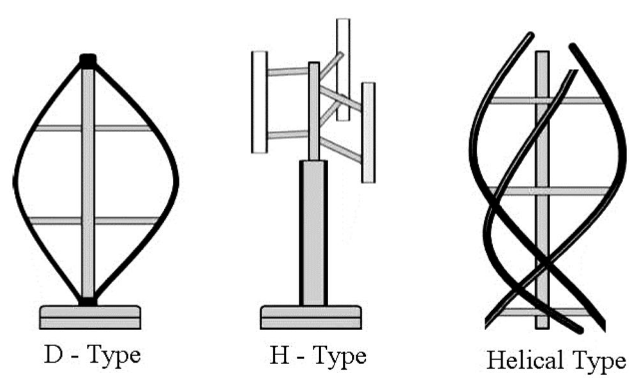


Fig. 9 Darrieus Type VWT (Islam et al. 2008)

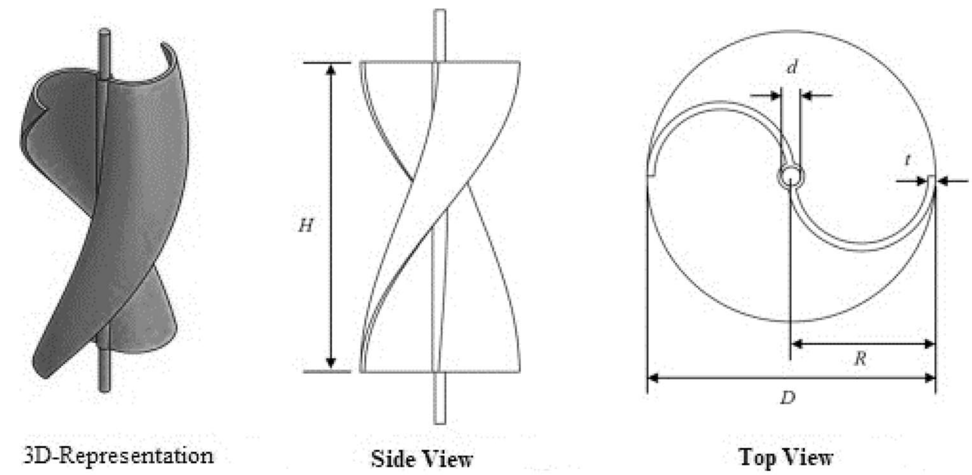


Fig. 10 Savonius Type VWT (Cuevas-Carvajal et al. 2022)

4.2 Types of Wind Turbines

Wind turbines are divided into two distinct classes. They are a) Horizontal Axis Wind Turbine (HWT), b) Vertical Axis Wind Turbine (VWT)

4.2.1 Horizontal Axis Wind Turbine (HWT)

In HWT, the axis of rotation of the wind blades is parallel to the air stream. The heavy nacelle, which is situated at the top of the tower, houses the generator, gearbox, and other components. The design and installation are complex in HWT. The yaw control mechanism is critical for adjusting the rotor around a vertical axis in order to maintain it facing the wind. The HWT always produces constant power and is more reliable. The tip speed ratio and power coefficient are high. The main drawbacks of these wind turbines are their difficulties in installation, noise, and vibration at the time of operation (Knudsen and Nielsen 2012). HWT configurations are mostly used in large wind turbines on-shore and off-shore. Due to composite wind turbines, which are less in weight, noise creation, and vibration, the HWT also be used in smart cities like urban environments (Xu et al. 2021). Figure 8 shows the HWT placed over the individual home on the rooftop.

4.2.2 Vertical Axis Wind Turbine (VWT)

In VWT, the axis of rotation of wind blades is perpendicular to the air stream. Therefore, the nacelle is not needed for this type of turbine. Because the generator, gearbox, etc., are placed on the ground. As a result, designing and installing VWT in an urban environment becomes simple. The rotor orientation is

Fig. 11 Hybrid Solar-Wind Energy Harvesting System (2022)

not necessary for this type of turbine. The wind can be used to create electricity in these turbines from any direction. But the tip speed ratio and power coefficient are very low for these turbines. So, VWT is more suited for low-power applications. Another important advantage of this type of turbine is that they are less in weight, installation and making costs are cheap, and they can be placed anywhere easily (Bhutta et al. 2012). The main drawback of VWT is that it is not having the self-starting capability. It needs an additional mechanism to start from the stationary position. In addition to that, if the blades are running at a very high-speed cause permanent damage to the entire system.

There are two types of VWT. They are 1. Darrieus Wind Turbine, 2. Savonius Wind Turbine. The Darrieus type of wind turbine turns the shaft using lift forces. This type of wind turbine is further classified as D-type, H-type, and Helical type. Figure 9 shows the Darrieus type VWT. The Savonius type of wind turbine has cups that are pushed by the direct wind force. Figure 10 shows the 3-dimensional representation and side and top views of the Savonius-type VWT.

5 Hybrid Solar-Wind Power Harvesting in Smart Cities

Solar and Wind energy system are used individually mean it has some drawbacks. The sunlight, wind direction, and wind speed are not steady and constant throughout the year. In such cases, if any stand-alone system fully depends upon any one of the individual systems means they may not have the required amount of power. In addition to that, in smart cities like urban environments, the chances for shading effect and wind speed degradation are possible by many factors. In such cases, a Hybrid system is proposed (Karthick et al. 2021). Mainly Hybrid system combines any two energy sources and generates electricity. The most preferable and easily accessible energy sources are solar and wind. These can be combined, and a Hybrid Solar-Wind power harvesting system can be created, and it can be used in a smart city-like urban environment. This type of system provides a more reliable source of power supply to the residents. Figure 11 shows the Hybrid Solar – wind power harvesting system installed in the individual home.

5.1 Hybrid Solar-Wind Power System – Supervisory Controller

The schematic (Fig. 12) shows the controllers used in the Hybrid Solar-Wind system. The Maximum Power Point Tracking (MPPT) controllers are mostly used to control the power outputs from the wind turbine and Solar panel. Which is then stored in the battery, converted as AC, and supplied to the loads. Additionally, the current study will provide a supervisory controller that will oversee the functioning of the hybrid Solar-Wind unit with a backup system in both grid-connected and stand-alone modes (Lubosny and Bialek 2007). Figure 13 shows a detailed diagram of the Supervisory Control of Hybrid Solar-Wind Energy Systems.

The algorithm of the supervisory controller is shown using a flowchart in the following Fig. 14.

Solar Cells and wind generators generate electricity using solar and wind energy, respectively. The system can be controlled using supervisory control (Singh et al. 2021). Four major system components are involved in configuration and control. They are Wind Generator Side Control, Solar Cell side Control, Battery Bankside Control, and Inverter side Control. The supervisory controller checks the batteries before driving the system into starting mode to begin operation. The utility grid is examined, and if it is, the controller turns it on or instructs the equipment to operate in standalone mode. According to the algorithm, the secondary system modes in a stand-alone system are determined by the batteries' State of Charge (SOC). The controller continuously checks the grid's availability, and if it is, it changes the system to the grid-connected mode. The system switches to a lower power mode if the power generated at any given time exceeds the rating. In

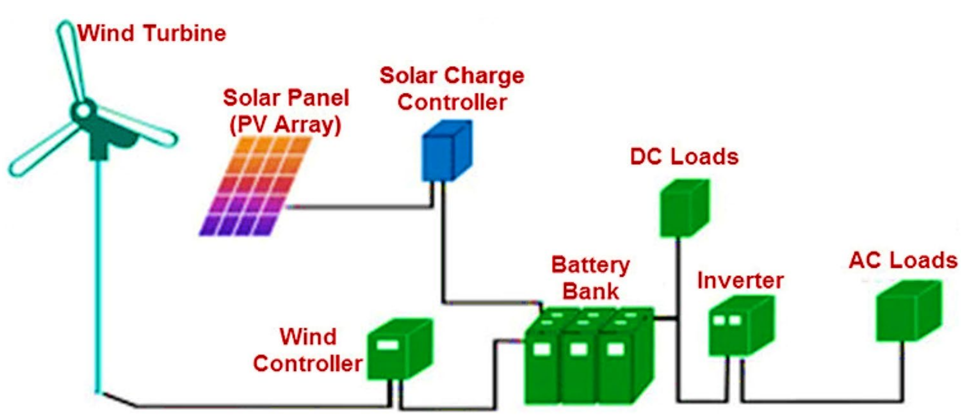


Fig. 12 Controllers in Hybrid Solar-Wind Energy System

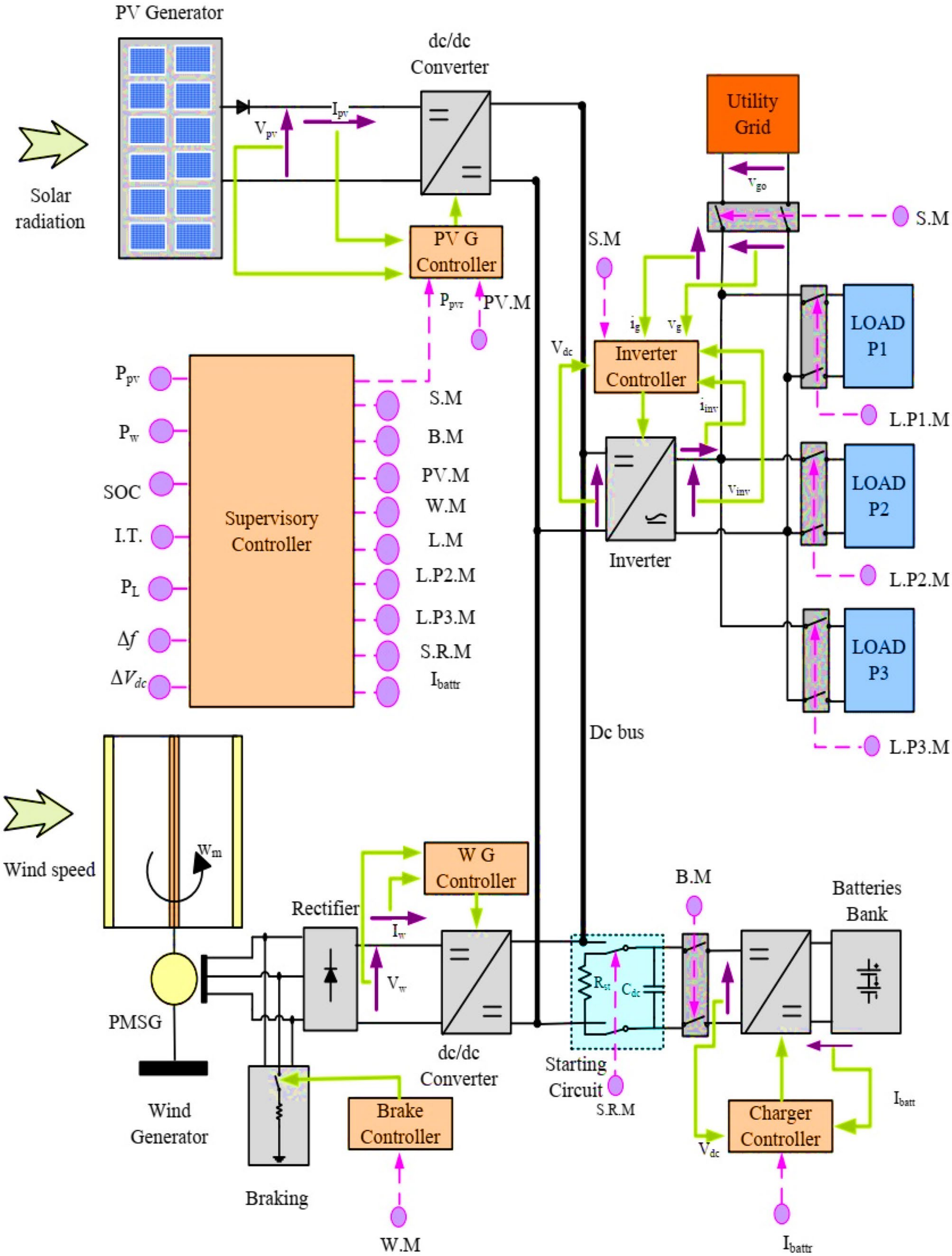


Fig. 13 Block Diagram of the Supervisory Control of Hybrid Solar-Wind Energy System

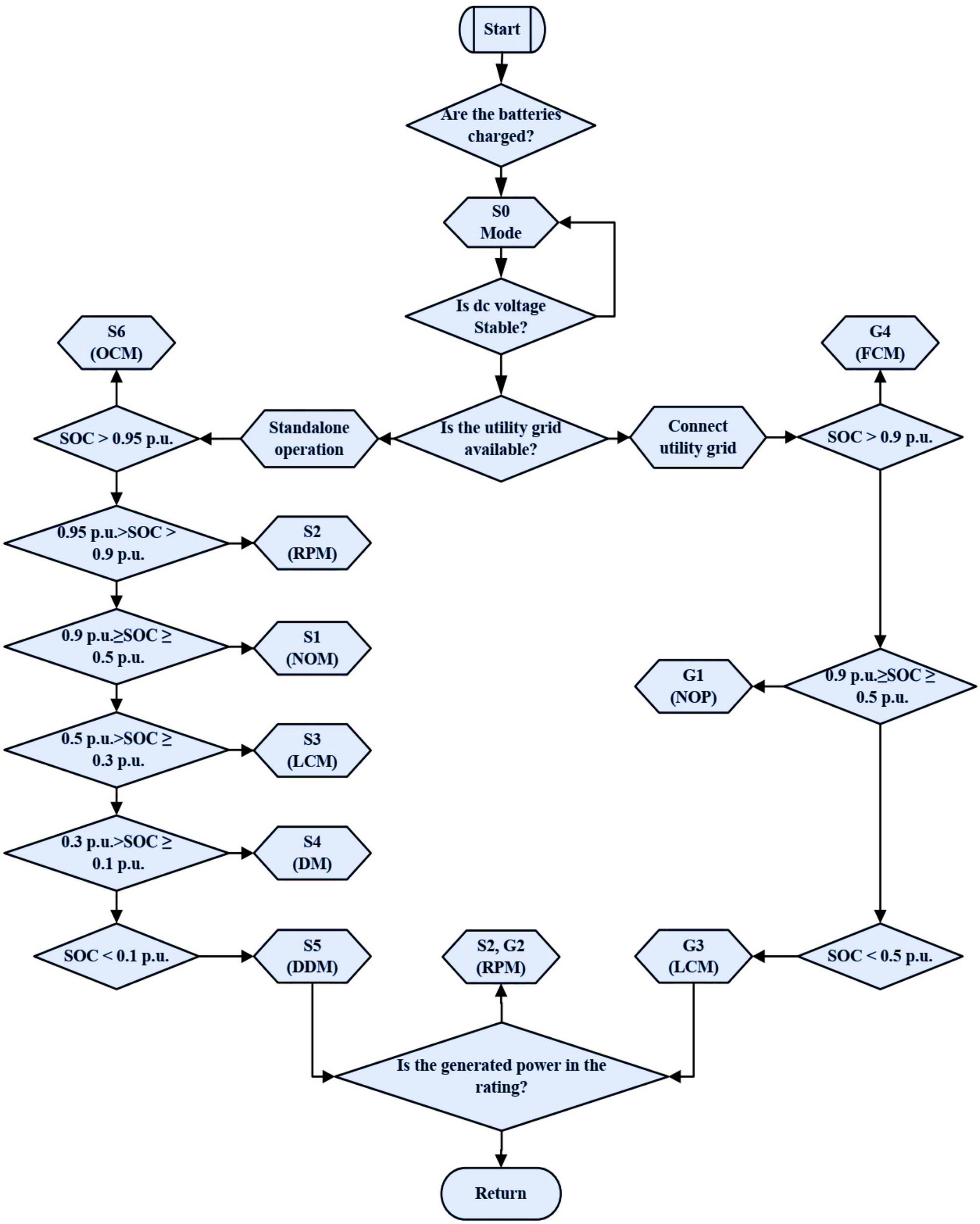


Fig. 14 Supervisory Control Algorithm

Table 2 The average output voltage of a 125Watts and 7A solar panel every month of the year 2021

Sl.No	Month	Average Output Voltage (V)
1	January	16
2	February	17
3	March	17.5
4	April	18
5	May	18.5
6	June	18.2
7	July	17.5
8	August	17
9	September	16.5
10	October	16
11	November	15.5
12	December	15

any mode of operation, the batteries are always charged to a minimum of 0.1 per unit; this guards against deep discharge and preserves some charge for the subsequent startup. The supervisory controller's constraints and inputs are all expressed as per-unit values. As a result, the supervisory controller will be competent to oversee systems with various system ratings. The controller will also be able to manage systems with a single renewable energy source or multiple sources. An extensive range of renewable energy systems that the supervisory controller can also supervise will be made possible by the modularity of the device.

Table 3 Solar Panel average output voltage and power during different times of the day in the month of June

Sl.No	Time of a Day	Average Output Voltage (V)	Average Power (W)
1	7 am	14	98
2	8 am	14.5	101.5
3	9 am	15	105
4	10 am	16	112
5	11 am	17.5	122
6	12 am	18	126
7	1 pm	18.2	126.5
8	2 pm	18.1	126.2
9	3 pm	17.8	125
10	4 pm	17	118
11	5 pm	16	112
12	6 pm	14	101.5

5.1.1 Wind Generator Side Control

A diode rectifier rectifies the wind generator's AC output power, controlled by a boost converter. At low and moderate wind speeds, the boost converter gives maximum power point tracking (MPPT), however, at high wind speeds, it stalls the generator, so limiting the power and rotor speed. A braking resistor is used to switch off the wind generator in response to a control signal from the supervisory controller.

5.1.2 Solar Cell Side Control

A dc/dc boost converter controls the solar cell, which is a non-linear dc source. This converter connects the solar cell to the MPPT system. In the following circumstances, Reduced Power Operation (RPO) is offered to minimise the system's generated power: a) If the generated power exceeds the ratings of the power electronics. As the temperature decreases, for instance, the solar generator's output can greatly exceed the datasheet rating. On some summer days, solar radiation can also reach extremely high levels, which causes the power output to surpass the ratings, b) The battery bank must be completely charged and the system must be in stand-alone mode to minimise periods of time when the renewable energy sources are disconnected.

5.1.3 Battery Bank Side Control

Because of their quick response times and high reliability, battery storage devices can be used in a plethora of situations. Battery storage technologies have recently improved dramatically as a result of the expanded application. In order to maintain the availability and stability of the system, the batteries are employed for a number of tasks, including power system frequency management (Raj 2016). Additionally, it is affordable to use battery storage devices as a temporary home backup. Integration of this system with standalone or grid-connected renewable energy systems is another extremely potential application. Battery storage is critical for maintaining a constant output power and increasing the system's overall availability.

5.1.4 Inverter Side Control

The supervisory controller is used to control the H-bridge single-phase inverter. Switching between stand-alone operation and grid-connected is accomplished with the controller (Jain et al. 2020). This inverter is controlled so that the following is ensured: 1) To maintain the constant voltage value in the DC bus; 2) International standards are followed in the modulation of the voltage and current waveforms; 3) Following the supervisor control signals, the load requirement is satisfied. These signals are used to control the inverter's reference currents, 4) To maintain the needed power factor, which is unity, the supplied power is regulated. A Phase Locked Loop (PLL) controller is

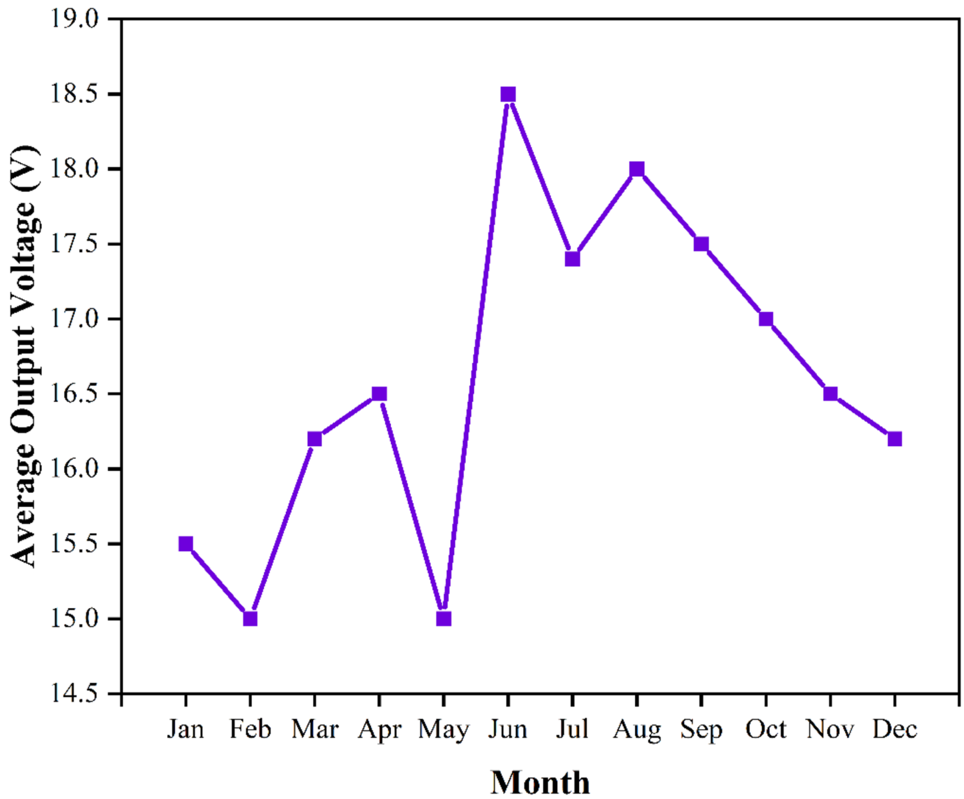


Fig. 15 Graphical representation of the output voltage variation of the wind turbine over the year 2021

used to align the reference current with the grid voltage, 5) The DC component injected to the grid is suspended by utilising the dc component measurement circuit, 6) When changing between modes of operation, the suggested system works as intended, and 7) The supervisory controller detects the islanding condition and drives the system appropriately.

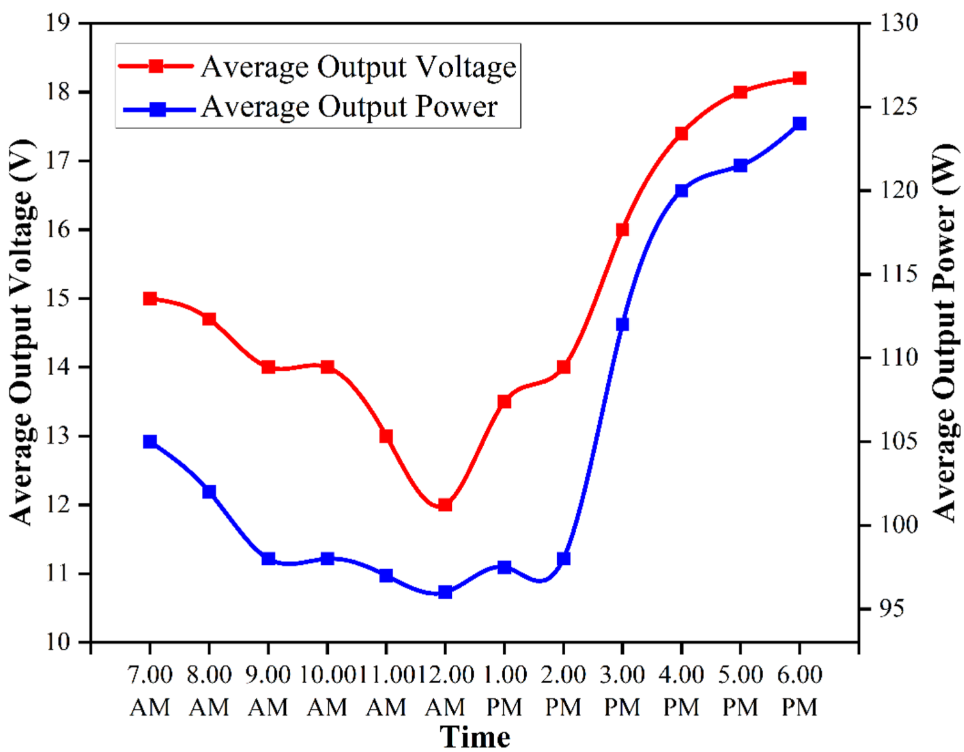


Fig. 16 Graphical representation of Average out voltage and power of a wind turbine in a single day in the month of June

Table 4 Average output power and voltage of Hybrid system in a single day in the month of June

Sl.No	Time of a Day	Average Output Voltage (V)	Average Power (W)
1	7 am	29	203
2	8 am	29.2	203.5
3	9 am	29	203
4	10 am	30	210
5	11 am	30.5	219
6	12 am	30	222
7	1 pm	31.7	224
8	2 pm	32.1	224.2
9	3 pm	33.8	237
10	4 pm	34.4	238
11	5 pm	34	233.5
12	6 pm	32.2	225.5

5.2 Comparison of Standalone Solar or Wind systems with Hybrid Solar-Wind Power Systems in Smart Cities

The solar panel is designed with a rating of 125 watts, and a current rating of 7A is installed on the rooftop (Location: Tirunelveli, Tamilnadu, India - 8°43'46.5"N 77°43'27.7"E). The average output voltage and power from the solar panel are measured and approximated in the year 2021 and simulated using a MATLAB/Simulink environment (Ishaque and Salam 2011). Table2 shows the output voltage of the standalone solar panel every month. Similarly, Table 3 demonstrates the solar panel's output power and the output voltage at different times on a particular day in the month of June.

The results revealed that the stand-alone solar panels harvest the maximum amount of energy from the sunlight with an output voltage of 18.5V in the month of May. It is also evident that in the afternoon, at 1 pm the solar panel extracts a maximum of power from the sunlight with an average output voltage of 18.2V and 126.5W. From the results, it is also clear that solar power generation is not constant throughout the year as well as in a single day.

Similarly, the wind turbine is also designed with a rating of 125 watts and 7 A with a power conditioner placed on the rooftop (Location: Tirunelveli, Tamilnadu, India - 8°43'46.5"N 77°43'27.7"E). The average output voltage and power from the wind turbine are measured and approximated in 2021 and simulated using a MATLAB/Simulink environment (Nath and Rana 2011). Figure 15 shows the voltage variation of the stand-alone wind turbine over the year in graphical representation. Similarly, Fig. 16 illustrates the wind power generation and voltage variation of the wind turbine in a single day in the month of June in a graphical format.

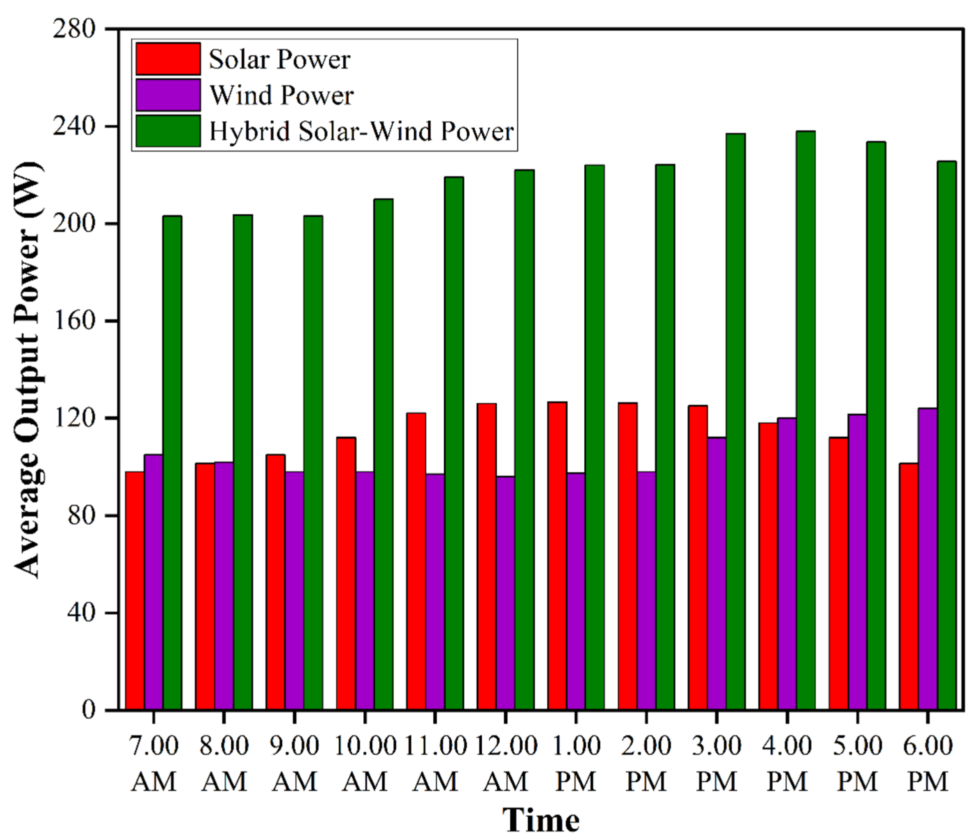


Fig. 17 Comparison of Hybrid System with Stand-alone system in terms of average output power on a particular day in the month of June

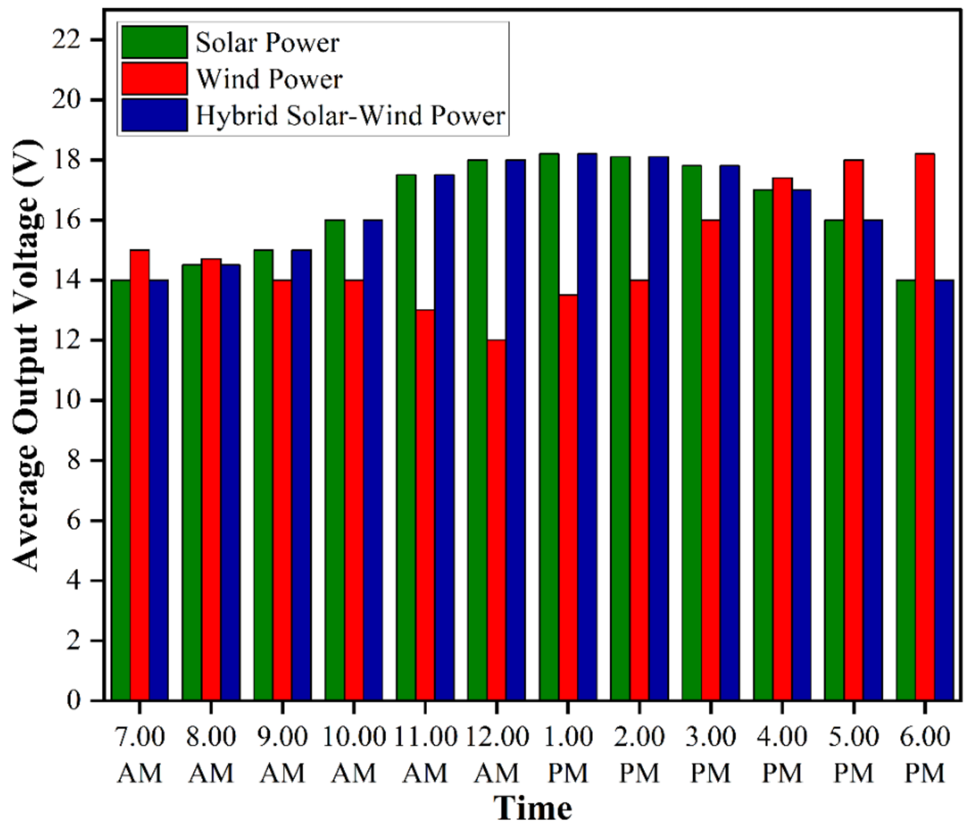


Fig. 18 Comparison of Hybrid System with Stand-alone system in terms of average output voltage on a particular day in the month of June

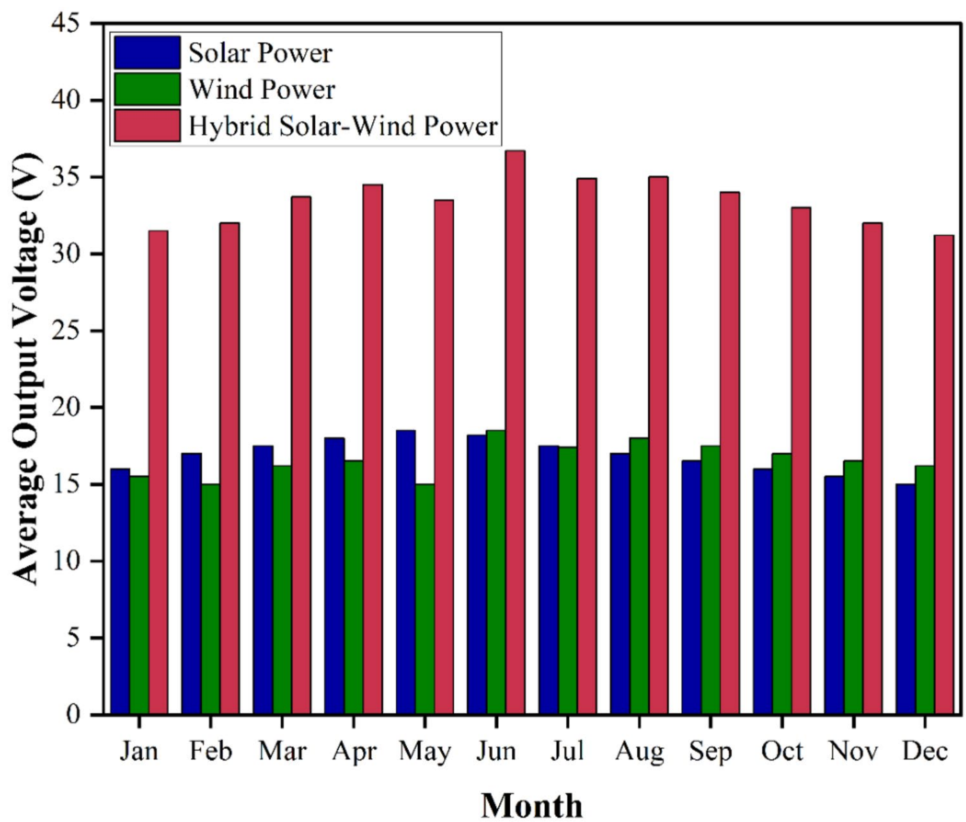


Fig. 19 Comparison of Hybrid System with Stand-alone System in terms of average output voltage in the different months of the year 2021

The results revealed that the stand-alone wind turbine generates the maximum amount of power in the month of June with a voltage of 18.5V. It is also evident that the power output and output voltage of a wind turbine in a single day in the month of June is 18.5V and 124W respectively. It is also proved that the stand-alone wind turbine's power output is continuously varying over the year as well as the day.

From the above analysis, we can conclude that the wind or solar is used as a stand-alone system the average output voltage and power during a day or over a year is not to be constant. The values are continuously varying. Therefore, the reliability of the system will also become a problem. To overcome this issue, the Hybrid Solar-wind power system is proposed. The hybrid solar-wind power system is installed on the rooftop (Location: Tirunelveli, Tamilnadu, India - 8°43'46.5"N 77°43'27.7"E). The average output voltage and power from the wind turbine are measured and approximated in 2021, and the same system is designed and simulated using a MATLAB/Simulink environment (Bouzelata et al. 2016). Table 4 shows the output power and voltage values of the Hybrid system. Figure 17 shows the comparison of the stand-alone system and the hybrid system in terms of average power generated in the month of June. Similarly, Fig. 18 compares the hybrid system and stand-alone system in terms of the average output voltage on the same day of the month of June. Figure 19 compares Hybrid System with Stand-alone System in terms of average output voltage in the different months of the year 2021.

The results revealed the supremacy of the Hybrid wind-solar system. When compared with stand-alone systems, the hybrid systems extract more amount of energy from the wind and sunlight at different times of a single day as well as all the months of the year. From this, we can infer that instead of using a stand-alone solar or wind turbine system, the hybrid system is highly beneficiary.

6 Summary and Conclusion

In the present work, the important green energy technology, such as solar and wind power technologies and their suitability in smart cities like urban environments is discussed. The PV cell and its operation and various types of PV cells used in these modern days are also discussed. Normally used different types of solar systems and the most suited one for smart cities are also discussed. In a similar way, wind power harvesting in the smart city-like urban environment is also detailed. The types of wind turbines and their construction are also discussed briefly. The stand-alone PV system or wind turbine system does not provide reliable power to consumers due to its limitations. To overcome these issues, the Hybrid solar-wind power system is proposed. In such a hybrid configuration, the control of solar panels and wind turbines based on the customer's requirement is complicated. Efficient supervisory control is proposed and discussed in the present work. The Solar and wind energy systems are designed using a MATLAB/Simulink environment. Their performance during a day and over a month is discussed. Similarly, the Hybrid Solar-Wind energy system is also designed, and its output results are compared with the stand-alone systems. The Hybrid Solar-Wind power systems showed better performance compared with individual systems and were more suited to the sustainable future smart cities like urban environments.

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Declarations

Consent to Publish Not Applicable.

Consent to Participation Not Applicable.

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