Planning for Urban Energy Needs with A PV/WT Integrated Low-Carbon Infrastructure: A Techno-Economic and Environmental Study

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Abstract

This study presents a techno-economic feasibility analysis of implementing an autonomous hybrid renewable energy system in a university building in Saudi Arabia. The system utilizes a combination of solar panels and wind turbines to generate electricity and a storage system to manage excess energy. The economic analysis includes cost-benefit analysis, payback period, and net present value. The results show that the proposed system has a positive net present value and a payback period of fewer than 10 years. The implementation of the system is expected to reduce the university's reliance on fossil fuels and decrease its carbon footprint. Overall, the findings suggest that the adoption of an autonomous hybrid renewable energy system is a viable and financially feasible option for the university.

Keywords: HOMER Software; Optimization; Solar energy; Wind energy; renewable energy.

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1. Introduction

The acceleration of climate change owing to greenhouse gas emissions such as carbon dioxide necessitates a transition to renewable energy sources. The usage of fossil fuels for power production and petroleum for our automobiles contributes significantly to atmospheric carbon dioxide levels. To offset these consequences, we must switch to the production of renewable energy. Solar photovoltaics (PV) is a technique that converts solar energy to electricity without emitting CO_2 into the environment. Utilizing sustainable energy infrastructure on a university campus may reduce greenhouse gas emissions and facilitate the transition to sustainable energy generation [1], [2].

Renewable energy generation has attracted considerable interest due to its superior sustainability and environmental benefits over fossil fuels. Solar and wind energy generation technologies are the most desirable options. Saudi Arabia has a significant capacity to produce electricity from renewable sources. El Khashab et al. analyzed the average daily sun radiation in Saudi Arabia [3]. The sun's radiation ranges between 4 and 7.5 kWh/m2, which is significantly higher than that of Europe. The Saudi Arabian government intends to generate 54 gigawatts of electricity from renewable sources by 2032 [4]. Utilizing renewable resources provides benefits for Saudi Arabia in reducing domestic energy consumption, and CO2 emissions, and increasing oil and natural gas export earnings.

Producing power from a single renewable resource, such as photovoltaic (PV) or wind turbines (WT), would result in additional issues owing to high investment costs, ecological limits, and reduced sustainability due to reliance on a single source [5]. Consequently, a collection of varied renewable resources, termed Hybrid Renewable Energy Systems (HRES), may provide more dependable and effective benefits. The capacity to incorporate renewable resources may outweigh the system's ecological concerns. They may also address the problem of energy availability in rural regions.

One of the great merits of HRES is to operate as a grid-connected or autonomous mode. The net cost of HRES plays a major obstacle to create electricity from renewable resources due to the high initial payment and maintenance cost of energy storage. At the autonomous mode of the microgrid, energy storage is required to totally achieve load energy demand which contributes to increasing the total cost. Wind energy is also subject to limitations due to wind speed fluctuation. When the wind speed is lower than the cut-in speed of the assigned wind turbine, there is no energy output because of insufficient torque exerted by the wind on the turbine blades. On the other hand, when the wind speed exceeds the rated cut-out speed, the control system will activate the braking system to wind turbines to protect the rotor of the wind's generator. Generally, a storage system plays an important role in operating renewable energy systems to achieve sustainability and reliability [6].

HRESs are used in grid-connected and stand-alone arrangements to fulfill the demand for power in distant rural and distinctive urban areas [7]–[11]. For HRES evaluation, many modeling and optimization techniques are utilized. Based on these methodologies, several optimization tools for the optimum design of HRES are created [12]–[16]. The primary goal of researchers is to specify the appropriate design and equipment size of HRES. The Hybrid Optimization Model for Electric Renewables (HOMER) program is one of the most effective methods for achieving this objective and has been applied by researchers from all around the globe [14], [17]–[20]. Multiple studies have analyzed the state-of-the-art research using HOMER for the simulation and optimization of HRESs from various perspectives [21], [22].

Numerous research on the optimum planning of HRESs in both off-grid and grid-connected modes with PV, WT, battery, and converter are reviewed. These studies indicate that the HRES based on both PV and WT is more efficient and less expensive than PV or WT systems alone [23]–[27].

2. Modelling Approach

This study presents a modeling approach for analyzing the performance of a hybrid off-grid photovoltaic (PV)/wind system for a small university building in Saudi Arabia. The proposed system consists of PV panels and wind turbines to generate electricity, and a battery storage system to manage excess energy.

2.1 Electric load profile

Figures 2 and 3 present the daily and seasonal load profile of the selected building. The daily load profile shows the hourly electricity demand of the building over 24 hours, while the seasonal profile shows the average daily demand over a year. The daily load profile is characterized by peak demand in the morning and evening hours when the building's occupants are using the most electricity for lighting, heating, and cooling. The seasonal profile shows that the building's electricity demand is higher in the warmer months when the occupants need more cooling. Overall, the daily and seasonal load profile provides valuable information for designing and sizing the proposed hybrid PV/wind system to meet the building's electricity needs throughout the year.

2.2 Solar energy resource

Figure 4 presents the scaled annual average of solar global horizontal irradiance (GHI) data obtained from the HOMER software. The data is collected from the study location (20°0.9'N, 41°28.3'E) using the latitude and longitude data entered the HOMER software. The figure shows that the solar GHI at the study location is highest in the summer months when the sun is shining directly overhead, and lowest in the winter months when the sun is lower in the sky. The figure also shows that the solar GHI varies throughout the day, with a peak in the middle of the day and a dip in the early morning and late afternoon. Overall, the solar GHI data provides valuable information for designing and sizing the PV panels in the proposed hybrid PV/wind system.

2.2 Wind energy resource

Figure 5 presents the wind resources of the selected area. The data is collected from the study location (20°0.9'N, 41°28.3'E) using the latitude and longitude data entered the HOMER software. The figure shows the wind speed and direction at the study location throughout the year. The figure indicates that the wind speed is highest in the winter months and lowest in the summer months. Overall, the wind resource data provides valuable information for designing and sizing the wind turbines in the proposed hybrid PV/wind system.

2.3 Solar module

In this study, Canadian Solar MaxPower CS6U-340M monocrystalline solar cell modules with a capacity of 340 Wp and an efficiency of 17.49% were selected. These modules have a 25-year lifespan. The selected module has costs of $845.5/kW for capital expenditures, $845.5/kW for replacement expenditures, and $10 for operations and maintenance per year.

2.4 Wind generator

In this study, a generic wind turbine with a capacity of 1 kW and hub height of 17 m were selected. These wind turbines have a 20-year lifespan. The selected module has costs of $7000 for capital expenditures, $7000 for replacement expenditures, and $70 for operations and maintenance per year.

2.5 Storage batteries

The Tesla Powerwall 2.0 is a high-performance battery storage system that can improve the performance of a microgrid by providing a reliable source of power during short-time disturbances and variations in solar irradiation. The use of multiple batteries in a string allows for greater flexibility in terms of capacity and output voltage, allowing the system to adapt to the needs of the PV and WT generation systems it is supporting.

The specific battery selected for this system has a capacity of 60 Ah and an output voltage of 220V, and a roundtrip efficiency of 89%, meaning that it can deliver a high level of power with minimal losses. The capital and replacement costs of these batteries are similar, at around $6500, and they are expected to have a lifespan of 10 years. This makes them a cost-effective choice for a microgrid battery storage system.

2.6 Inverter

The inverter is an essential component of a microgrid system, as it converts the direct current (DC) power generated by the solar panels into alternating current (AC) power that can be used by household appliances and other electrical equipment. In the proposed system, a 1 kW inverter was selected, with an efficiency of 95% and an initial capital cost of $300 per kW. The inverter also has an annual operation and maintenance (O&M) cost of $2.

2.7 Analysis

System designers utilize the sophisticated software application HOMER to evaluate the feasibility and economic viability of microgrid systems. It is intended to reduce the net present and operating costs of a system based on sensitivity inputs and other pertinent information.

For the economic analysis, HOMER evaluates a variety of criteria, such as the yearly discount rate, annual inflation rate, project lifespan, and the market-based cost of each component. In the case of the proposed microgrid system, a discount rate of 2%, an inflation rate of 3%, and a project duration of 25 years were employed. This enables HOMER to deliver a thorough and accurate study of the system's economic performance.

3. Results and discussion

According to Table 1, the best possible design for the system would include a photovoltaic (PV) system with a capacity of 50 kW, as well as four wind turbines, forty strings of Tesla Powerwall battery banks, and a 19.3 kW converter.

The Total Net Present Cost (TNPC) is a measure of the total cost of a renewable energy system over its lifetime, considering factors such as initial capital costs, operating and maintenance costs, and the time value of money. In this case, the proposed system has a TNPC of $807,566.10, which means that the total cost of the system over its lifetime is estimated to be $807,566.10.

The Levelized Cost of Energy (LCOE) is a measure of the average cost of generating electricity from a renewable energy system over its lifetime. It is typically expressed in dollars per kilowatt hour ($/kWh). In this case, the proposed system has an LCOE of $0.452/kWh.

The operating cost is the cost of operating and maintaining the renewable energy system on an ongoing basis. In this case, the proposed system has an operating cost of $16,752.75.

Table 2 provides an overview of the costs associated with the proposed system. The Tesla Powerwall battery has the highest capital expenses of $260,000 and the highest replacement costs of $602,664.56 correspondingly. However, the cost of operation and maintenance for the solar photovoltaic system is the greatest of all the system components.

It appears that the proposed system can produce a total of 95,914 kWh of electricity per year. Of this total, 96.7% is produced by the photovoltaic (PV) system, while 3.34% is produced by wind turbines (WT). This means that the PV system is the dominant source of electricity in the proposed system, while the WT contributes a smaller but still significant amount.

The excess electricity of the proposed system is 27.6%, which means that 27.6% of the electricity produced by the system is not used by the end user. This excess electricity can be sold back to the grid or used to power other loads. The unmet electric load of the proposed system is 0.0768%, which means that

0.0768% of the total electricity demand is not met by the system.

Figure 6 shows the monthly electric production from the proposed system. This can provide useful information about the system's performance over time, including its seasonal variation and its response to changes in weather and other factors. This information can be used to identify potential issues and optimize the system's performance over time. Figure 7 contains the following three graphs depicting the power output profiles of the PV system, the WT, and the battery bank.

4. Conclusion

Renewable energy is an important source of clean, reliable, and affordable energy that can be used to meet the needs of small university buildings and other facilities. Renewable energy sources, such as solar and wind power, are abundant, widely available, and produce little or no greenhouse gas emissions, making them a sustainable and environmentally friendly alternative to fossil fuel-based energy sources.

The use of renewable energy can provide several benefits to small university buildings, including:

Cost savings: Renewable energy systems can be cost-effective over the long term, especially when compared to fossil fuel-based systems. Renewable energy sources are typically free to use, and their costs are relatively stable over time, which can help to reduce the overall cost of energy for a small university building.

Reliability: Renewable energy systems can be designed to be highly reliable, providing a consistent and reliable source of electricity even when the grid is unavailable or unstable. This can be especially important for small university buildings that rely on electricity for critical functions such as lighting, heating, and cooling.

Environmental benefits: Renewable energy systems produce little or no greenhouse gas emissions, making them a sustainable and environmentally friendly alternative to fossil fuel-based energy sources. This can help to reduce the environmental impact of small university buildings and contribute to a healthier, more sustainable future.

Economic benefits: The use of renewable energy can support local economic development by creating jobs and supporting local businesses. Renewable energy systems can also generate revenue by selling excess electricity back to the grid, which can provide additional financial benefits to small university buildings.

Overall, the use of renewable energy is an important and increasingly viable option for providing clean energy to meet the needs of small university buildings and other facilities. Renewable energy systems can provide cost savings, reliability, environmental benefits, and economic benefits, making them an attractive option for small university buildings looking to reduce their energy costs and improve their sustainability.

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Table 1: Optimal system configuration.

Component	Name	Size	unite
PV	CanadianSolar MaxPower CS6U-340M	50.0	kW
Wind Turbine	Generic 1 kW	4	unit
Storage	Tesla Powerwall 2.0	40	strings
System Converter	System Converter	19.3	kW
Dispatch strategy	HOMER Cycle Charging		

Table 2: Optimal system cost summery.

Name	Capital	Operating	Replacement	Salvage	Total
CanadianSolar MaxPower CS6U-340M	$42,275	$14,225	$0.00	$0.00	$56,500
Generic 1 kW	$28,000	$7,966	$34,033	-$26,801	$43,198
System Converter	$5,782	$1,097	$6,693	-$2,460	$11,112
Tesla Powerwall 2.0	$260,000	$0.00	$602,665	-$165,909	$696,756
System	$336,057	$23,288	$643,390	-$195,169	$807,566

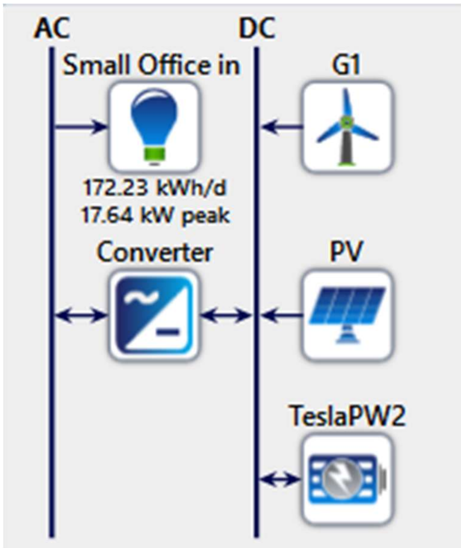

Figure 1. A schematic diagram of the proposed system.

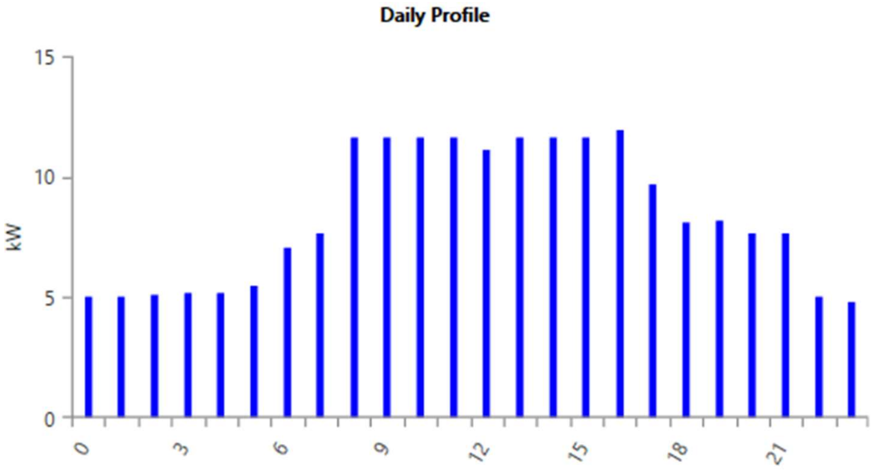

Figure 2. The daily load profile of the selected building

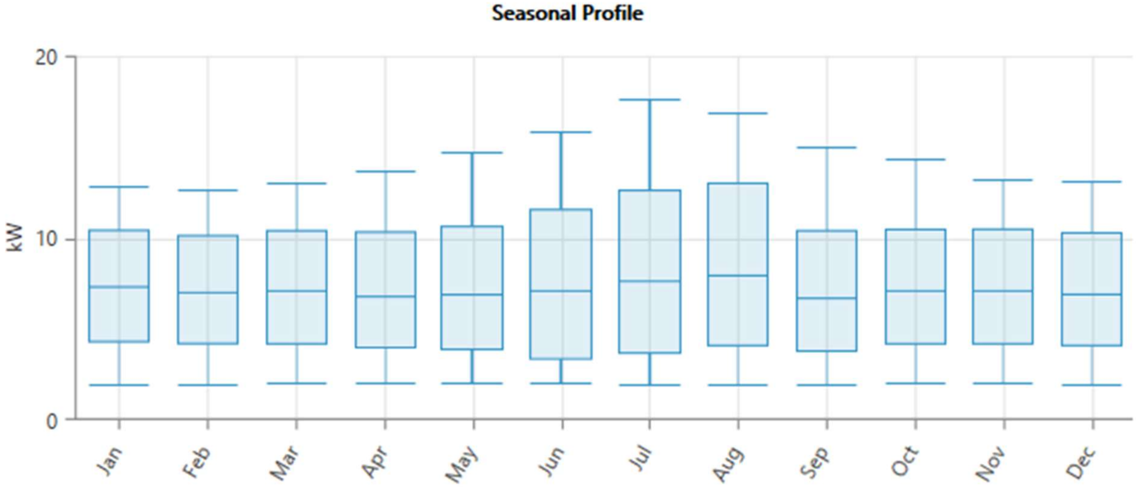

Figure 3. The seasonal load profile of the selected building

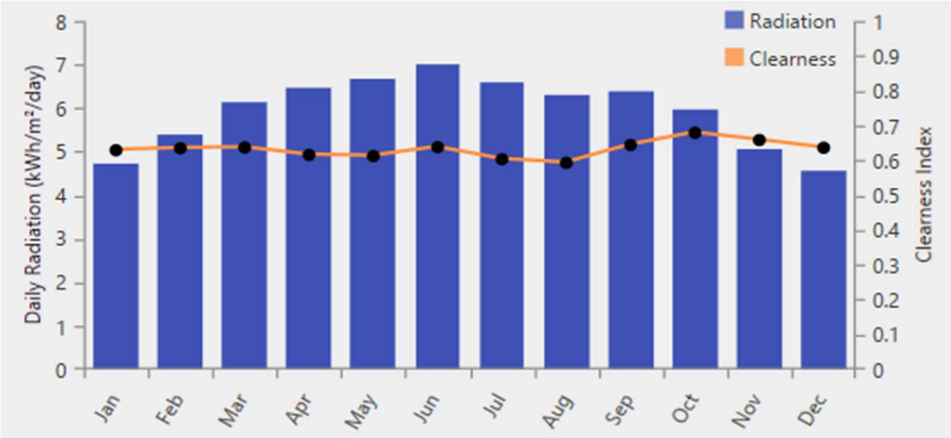

Figure 4. The monthly average solar irradiance data of the selected area.

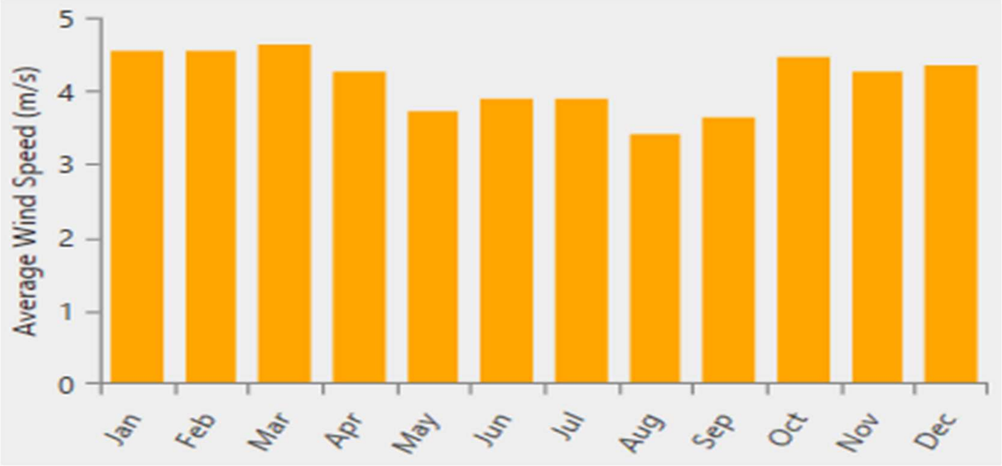

Figure 5. The monthly average wind speed data of the selected area.

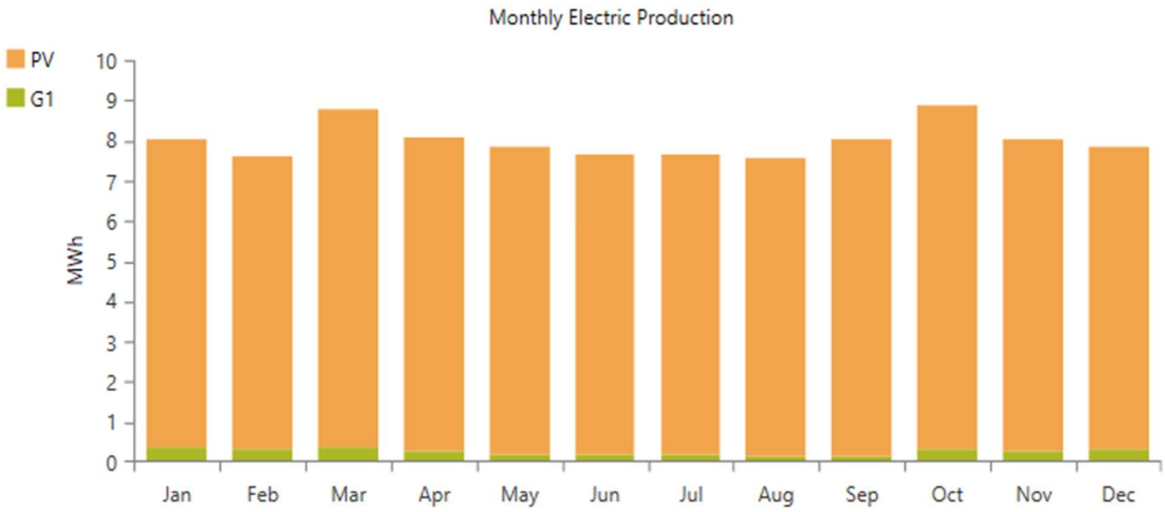

Figure 6. The monthly electric load production of the proposed system.

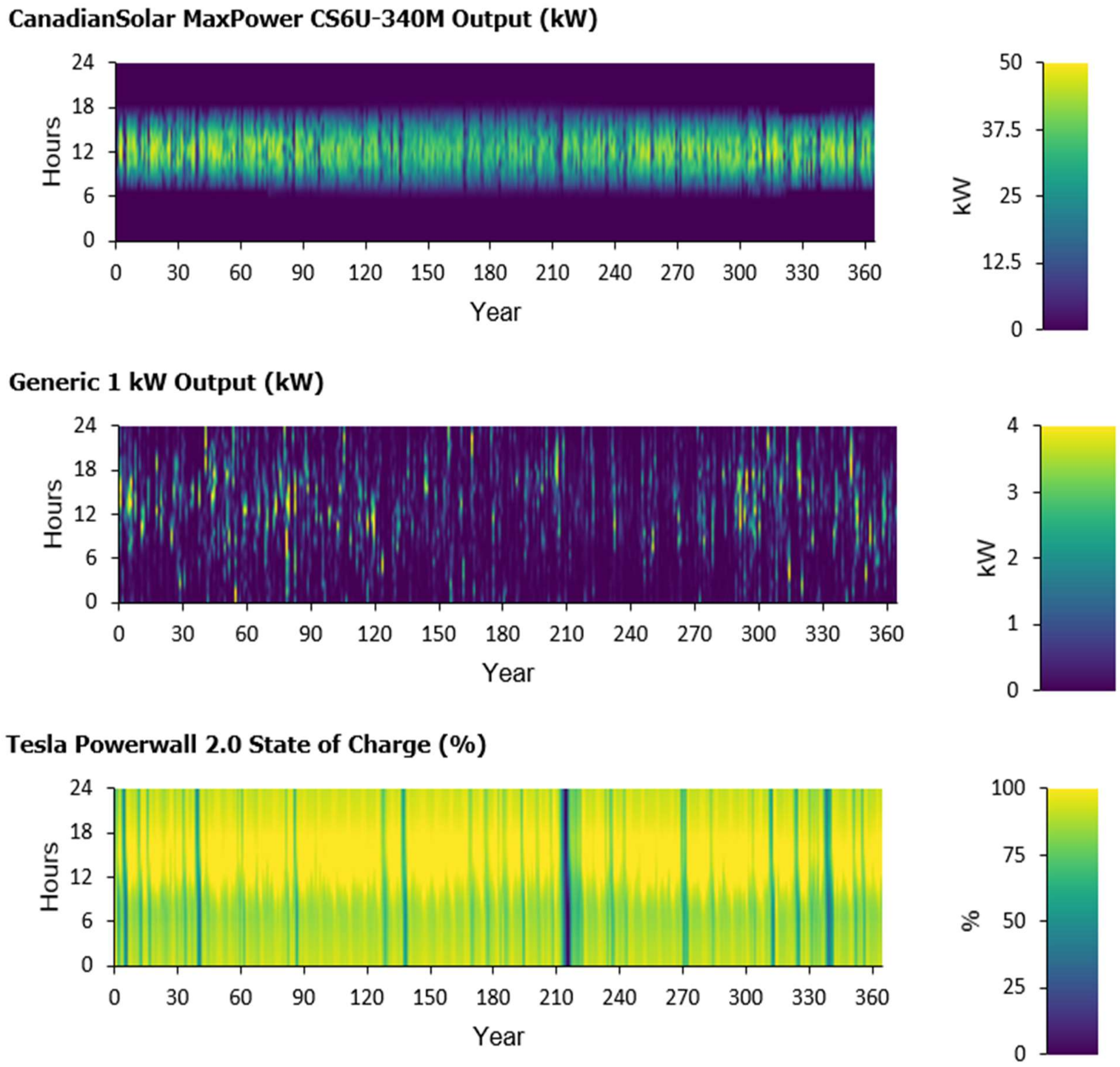

Figure 7. The power output profiles of the PV system, the WT, and the battery bank