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Optimisation of Microgrid by HOMER Pro Software Design: Innovative Approach and Performance Evaluation

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Abstract
This study analyses the performance of a renewable energy-based microgrid with the integration of Canadian Solar MaxPower CS6X-325P and the primary electricity grid. The findings demonstrate that solar panels can supply more than 50% of the annual energy demand, with maximum penetration during sunny months. The PV system with an installed capacity of 2.24 kW produces 2,731 kWh per year. Dependence on the electricity grid occurs during low irradiance periods, but there is no supply shortage for the load. The strong linear relationship between solar irradiance and PV power output indicates high efficiency in energy conversion. The findings also show that the system successfully sells excess energy to the grid when production exceeds consumption. This study emphasises the potential of microgrid systems in maximising the use of renewable energy, although increased storage capacity is needed to reduce dependence on the conventional grid.

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1. Introduction
Renewable energy is increasingly becoming a top priority in the global electricity system, especially as a solution to reduce carbon emissions and dependence on fossil fuels. Microgrids integrating renewable energy sources such as solar and wind with conventional electricity networks have proven to provide a stable and sustainable electricity supply. This system allows for emission reductions and supports the reliability of electricity supply, especially in remote areas or in times of energy crisis (da Silva et al. 2016; Valasai et al. 2017; Kabeyi and Olanrewaju 2022). In this context, renewable energy-based microgrids are increasingly being used, especially with the integration of solar panels. The Canadian Solar MaxPower CS6X-325P solar panel is one of the reliable technologies for generating electrical energy from solar radiation (Ahmed et al. 2022; Omidi and Iqbal 2022; Miky et al. 2023). With a capacity of 2.24 kW, this panel can produce sufficient power to meet daily electricity needs in a microgrid. This system maximises renewable energy by combining energy generated from the sun and the primary electricity grid, a backup for insufficient renewable energy (Vivas et al. 2018; Deng and Lv 2020; Infield and Freris 2020). This study aims to analyse the performance of the solar panel-based microgrid system and measure its efficiency throughout the year.

The main challenge in implementing renewable energy-based microgrids is the fluctuation of energy production, which depends on weather conditions and solar radiation variations (Kumar and Bhimasingu 2015; Mojumder et al. 2022; Hai et al. 2023). Therefore, using the conventional electricity grid as a secondary energy source is essential to maintaining the reliability of the energy supply. This study examines how the Canadian Solar MaxPower CS6X-325P-based microgrid operates annually, focusing on renewable energy penetration and interaction with the primary electricity grid. The study also analyses the effectiveness of microgrids in selling excess energy generated back to the grid and their impact on operating costs (Aziz et al. 2020; Ahmad and Zhang 2021; Prevedello and Werth 2021). The relationship between solar radiation and power output from solar panels is essential in understanding the system's efficiency. In addition, the energy storage capacity and its crucial role in increasing energy independence from renewable sources is evaluated.

The simulation and analysis results demonstrate that renewable energy can meet more than 50% of the annual energy demand, with maximum penetration during the months with high solar radiation. On the other hand, grid usage increases during bad weather or at night when renewable energy production decreases (Engeland et al. 2017; Erdiwansyah et al. 2019; Kabir et al. 2024). This underlines the importance of energy storage capacity in reducing dependence on the grid. Thus, this study provides a comprehensive view of the potential and challenges of operating solar panel-based microgrids (Ahmad and Alam 2018; Mah et al. 2021; Yaqoob et al. 2022). In addition, these results provide important insights for further developing more efficient microgrid systems, both technologically and economically, to support the transition to a broader and more sustainable use of renewable energy.

This study aims to evaluate the performance of renewable energy-based microgrids, explicitly using the Canadian Solar MaxPower CS6X-325P, in meeting energy needs efficiently and sustainably. The focus is to analyse the penetration of renewable energy, interaction with the primary electricity grid, and system efficiency in converting solar radiation into usable electricity. In addition, this study observes how the excess power generated can be sold back to the grid and its impact on operational cost efficiency. The novelty of this study lies in the detailed analysis of the relationship between global solar radiation and solar panel power output, as well as the evaluation of the overall system performance throughout the year. This study also offers new insights into the role of energy storage capacity in increasing the independence of microgrids from the conventional electricity grid, making a significant contribution to developing more efficient and environmentally friendly microgrid systems.

2. Methodology

The microgrid scheme combining three energy sources: the primary electricity grid, solar panels (CS6X-325), and wind turbines (XL1), with energy conversion and storage is presented in **Fig. 1**. The main electricity load uses 11.27 kWh of power per day with a peak consumption of 2.39 kW. While the converter transforms direct current (DC) from the solar panels into the alternating current (AC) that the load requires, the wind turbines and solar panels each independently produce electricity. The wind turbine that produces AC electricity is also connected to the converter, which directs energy to storage or the load. The energy storage system, a battery (Dis12V), stores excess energy from renewable sources and can supply electricity when the primary source is insufficient. If renewable energy and batteries cannot meet the load demand, electricity can be drawn from the primary grid. This design ensures optimal use of renewable energy, maximises efficiency, and provides a stable power backup for electrical loads.

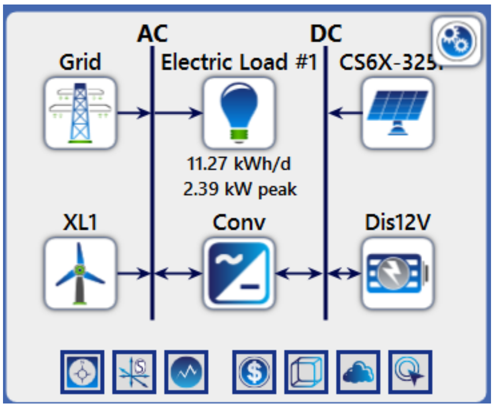

Fig. 1. Microgrid design diagram schematic

In addition, this microgrid displays flexibility in energy management with a conversion and storage system. The converter allows smooth integration between DC (solar panels) and AC (wind turbines and the primary grid) energy sources, ensuring the compatibility of the currents required by the electrical loads. Batteries are crucial in providing energy availability, mainly when solar panels or wind turbines cannot produce enough power, such as at night or when the wind is not blowing. With an intelligent system like this, the microgrid can balance energy production, storage, and consumption, reducing dependence on the primary grid and increasing the use of renewable energy.

3. Result & Discussion

Table 1 above presents data on energy production and consumption in the microgrid system for one year, divided into several categories. In the production section, there are two primary sources, namely the Canadian Solar MaxPower CS6X-325P solar panel with an annual production of 2,731 kWh or 51.3% of the total output, and electricity purchased from the primary electricity grid of 2,592 kWh or 48.7% of the total annual production. Thus, the total energy available in the system is 5,323 kWh per year, indicating that this microgrid uses almost half of the energy sourced from the primary grid and the rest from renewable energy through solar panels. Regarding energy consumption, the main electrical load of the AC primary load consumes 4,113 kWh per year or 79.3% of the total energy generated. There is no consumption on DC primary or deferrable load, which means that the entire load of this system is based on alternating current (AC). In addition to consumption by the load, there is also a sale of energy back to the grid of 1,073 kWh per year, representing 20.7% of the total energy. The total annual energy consumption is 5,186 kWh, almost equal to the total energy this microgrid system produces.

Table 1. Energy production and consumption data

Production	Unit kWh/year	Unit %
Canadian Solar MaxPower CS6X-325P	2.731	51.3
Grid Purchases	2.592	48.7
Total	5.323	100
Consumption	**Unit kWh/year**	**Unit %**
AC Primary Load	4.113	79.3
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sale	1.073	20.7
Total	5.186	100
Quantity	**Unit kWh/year**	**Unit %**
Excess Electricity	0.0000320	0
Unmet Electric Load	0	0
Capacity Shortage	0	0
Quantity	**Value**	**Unit (%)**
Renewable Fraction		

The third section of the table shows some important metrics about the energy balance in the system. The amount of excess electricity generated is minimal, only 0.0000320 kWh per year, indicating that almost all the energy the system generates is used effectively. In addition, there is no unmet electric load, meaning the system can meet all energy demands throughout the year. There is also no capacity shortage, indicating that the generation and storage capacity in the system is sufficient for the annual energy demand. Finally, the renewable fraction value has not been listed in the table but can be calculated from the percentage of renewable energy production (solar panels) to total energy production. Based on the data, the contribution of solar panels of 51.3% shows that this system has a relatively high renewable fraction. This indicates that more than half of the energy the system uses comes from renewable sources, so this microgrid can be considered environmentally friendly.

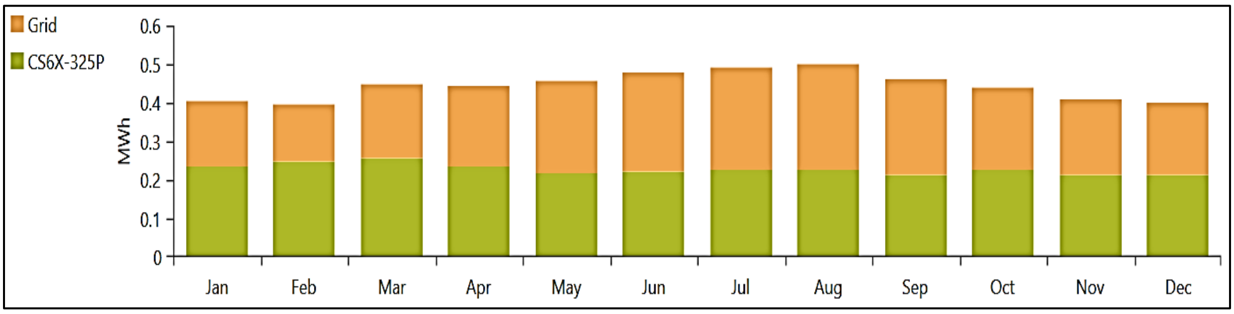

Fig. 2. Monthly Electric Production

Fig. 2 above shows a bar graph showing the contribution of two energy sources, namely the Grid (leading electricity network) and CS6X-325P (solar panels), in meeting monthly energy needs from January to December. Each bar shows the total monthly energy consumption divided into two parts: the bottom part in green for the contribution of solar panels, and the top part in orange for energy from the electricity network. Visually solar panels contribute consistently throughout the year. However, the proportion of energy tends to be greater during months with longer sunshine duration, such as from April to September. Meanwhile, the contribution from the grid is also stable throughout the year, with a more significant portion in the months with bad weather or winter, such as January, February, and December. This suggests that during these months, the production from solar panels may be lower, making the microgrid more dependent on the grid to meet its energy needs. This graph provides a clear picture of how the hybrid microgrid system effectively combines renewable and conventional energy throughout the year, with a higher reliance on the grid during winter and greater utilization of solar energy in summer.

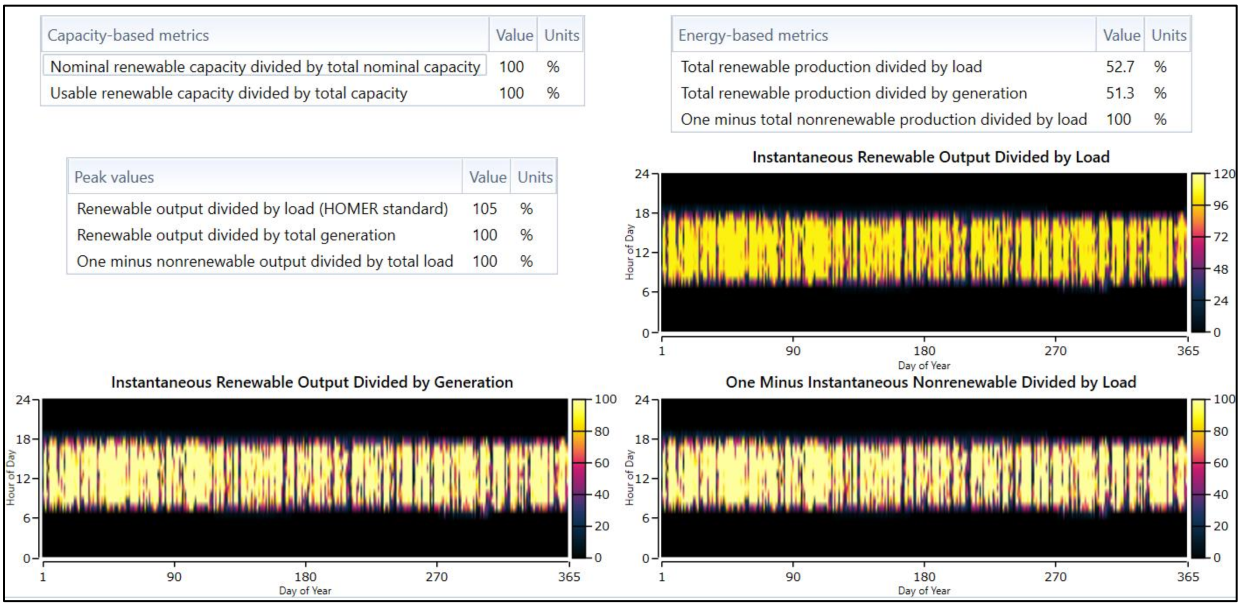

Fig. 3. Renewable of Penetration

Fig. 3 shows some metrics related to capacity and renewable energy in the microgrid system and a graph depicting the performance of renewable energy production against load and generation throughout the year. In the capacity-based metrics section, 100% of the nominal and usable capacity comes from renewable energy. This means that all the capacity available for use in this microgrid comes from renewable energy sources, which confirms the system's commitment to clean energy use. In the energy-based metrics section, the total renewable energy production compared to the load is 52.7%, indicating that more than half of the load's energy needs throughout the year are met by renewable energy. Meanwhile, compared to the total energy generation, renewable energy production reaches 51.3%, indicating that renewable energy contributes more than half of the total energy generated. Another metric that shows the remaining non-renewable energy compared to the load is 100%, indicating that energy that does not come from renewable sources is fully utilised when needed.

The graph at the bottom left shows instantaneous renewable output divided by load. The yellow to red colours indicate many times throughout the year when renewables exceed load (by more than 100%). This demonstrates that the microgrid system frequently produces more renewable energy than the load consumers. The lighter-coloured peaks indicate surplus renewable energy, which may be stored or sold back to the grid. The graph at the bottom right displays One Minus Instantaneous Nonrenewable Divided by Load, representing the percentage of nonrenewable energy the system uses to meet the load. Lower (darker) values indicate that nonrenewable energy is used minimally at certain moments, consistent with the system's goal of maximising renewable energy use. In other words, the system maximises renewable energy, with clean energy meeting most of the annual load.

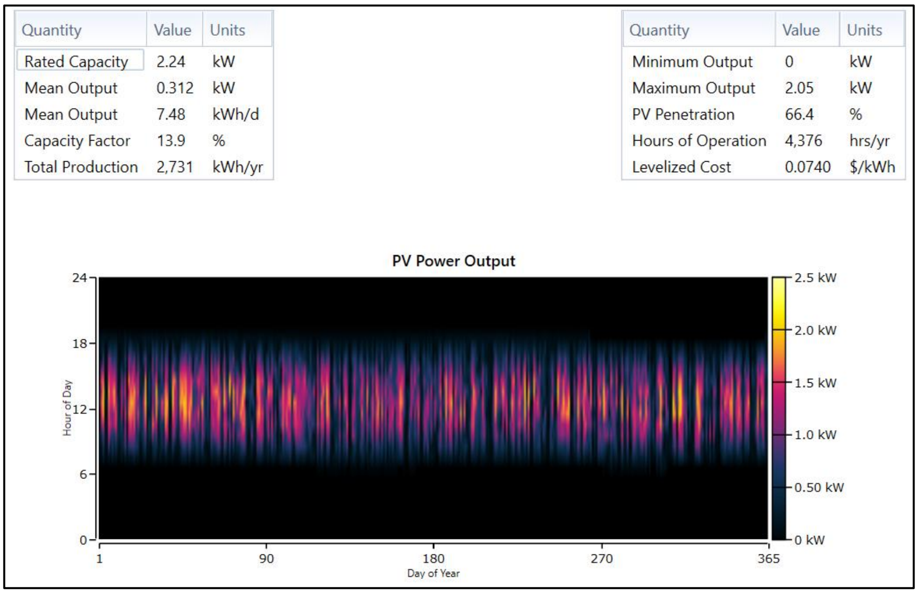

Fig. 4. Power Output of PV

Fig. 4 above shows the performance of the PV (photovoltaic) system or solar panels in a microgrid with several essential parameters related to capacity, production, and cost. On the left, the rated capacity of the PV system is 2.24 kW, which shows the maximum capacity the solar panels can produce. The mean output, or average annual power output, is 0.312 kW, which makes it an average of 7.48 kWh/day with a total yearly production of 2,731 kWh. The capacity factor of this PV system is 13.9%, which shows the percentage of use of the total maximum PV capacity during a year. On the right, the minimum PV output is 0 kW, indicating that the system does not produce power sometimes, especially at night or when sunlight is meagre.

Meanwhile, the maximum output reaches 2.05 kW, close to the maximum capacity. PV penetration reaches 66.4%, indicating that PV can meet most of the energy needs in the microgrid during its operation. With 4,376 operating hours per year, the system shows high efficiency with a levelized cost of $0.0740/kWh, which is relatively cheap for renewable power generation. The graph below shows the variation of PV power output throughout the year, where the intensity of the colour indicates the amount of power generated at each hour and day, with fluctuations following changes in sunlight intensity.

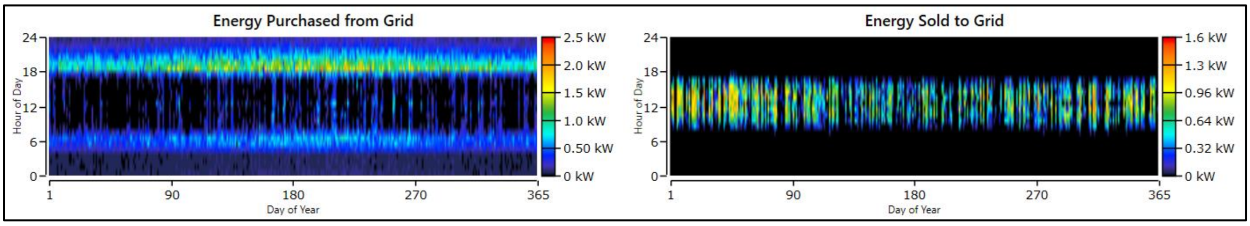

Fig. 5. Energy Purchased from Grid Compare Energy Sold to Grid

Fig. 5 above shows two graphs relating to energy purchased from the primary electricity grid (left) and energy sold back to the grid (right). The energy purchased from the grid graph shows fluctuations in energy purchases from the grid throughout the year at each hour of the day. Lighter colours, such as green to yellow, indicate periods of higher energy purchases, while blue colours indicate lower usage. Overall, there is a consistent pattern of energy purchases throughout the year, with higher purchases during the day, especially when energy demand is high or when renewable energy production (such as solar panels) is low. The energy sold to the grid graph shows the energy sold back to the grid from the microgrid. Lighter colours, such as yellow to orange, indicate periods when more energy is sold, while blue indicates lower sales. This graph shows that energy sales to the grid are more volatile than purchases, with sales occurring more frequently during the day and less frequently at night. This suggests that when renewable energy production (such as solar panels) exceeds load demand, excess energy is sold to the grid, especially during the sunnier months or when load consumption is low.

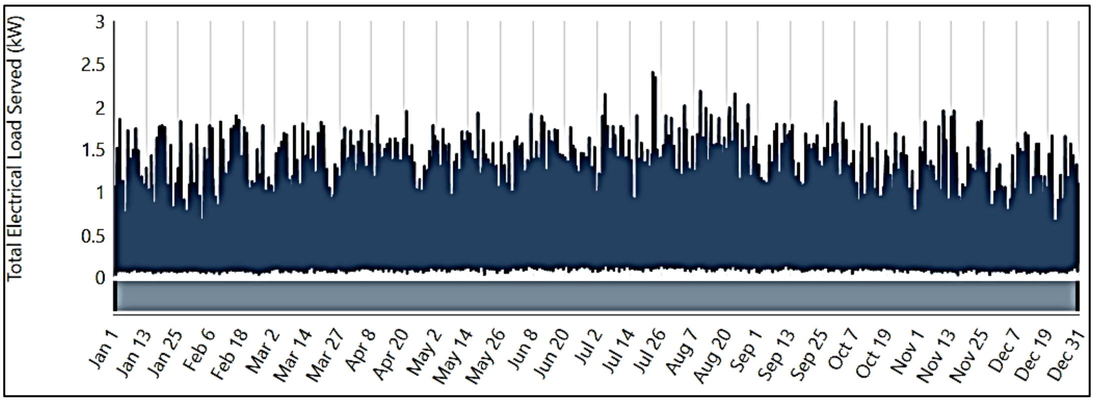

Fig. 6. Total of Electricity Load per year

The time-series graph in **Fig. 6** above displays the annual kilowatts (kW) of electrical load the microgrid system served. The graph shows daily load fluctuations from January to December, with the vertical axis showing electrical load levels up to 3 kW. The darker areas represent the relatively constant base load, while the higher, sharper peaks represent peak load periods when energy consumption reaches its highest level during the day. This load pattern shows that electricity consumption varies daily, with some days having significantly higher loads than others. This graph shows that the microgrid system experiences a reasonably stable load throughout the year despite significant daily fluctuations, especially during peak periods. It is expected to see periods of high consumption, which may result from intense domestic or commercial activity. A constant base load indicates a minimum electricity demand constant throughout the year. In contrast, peaks indicate spikes in electricity demand that may require additional capacity from the grid or energy storage systems to meet the demand.

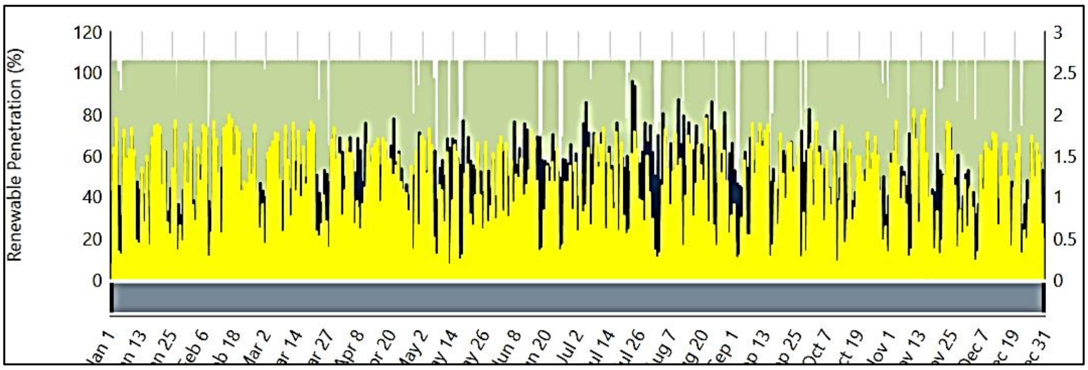

Fig. 7. Renewable Penetration

Fig. 7 above illustrates the renewable energy penetration (%) throughout the year in a microgrid system, with the percentage scale on the left axis and the total electricity load (kW) scale on the right axis. This graph shows how much renewable energy meets the daily electricity load. Yellow represents a lower renewable energy proportion, while green represents renewable energy penetration approaching or reaching 100%. The frequent fluctuations in the graph indicate that renewable energy penetration varies significantly over time. In general, it can be seen that there are many periods when renewable energy penetration approaches 100%, especially during the day when solar panels produce the most electricity. However, there are also many moments when renewable energy penetration drops significantly, indicating that renewable energy cannot always fully meet the electricity load. This can happen at night or when weather conditions do not support energy production from renewable sources. This figure illustrates the dynamics of a microgrid system in maximizing the use of renewable energy while also showing the challenges in achieving full penetration.

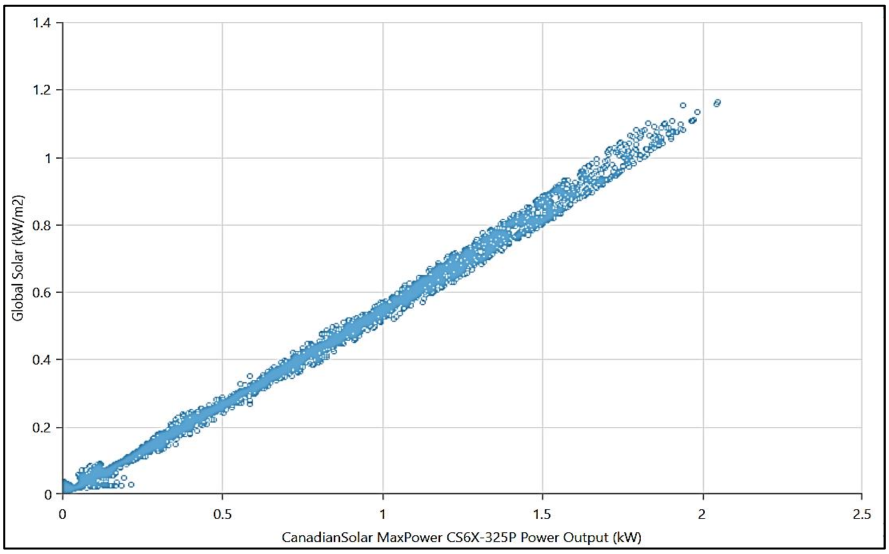

Fig. 8. Global Solar versus Canadian Solar Max Power

Fig. 8 above is a scatter plot showing the relationship between the power output of the Canadian Solar MaxPower CS6X-325P (horizontal axis) and global solar radiation (global solar radiation in kW/m²) on the vertical axis. The data shows a robust and linear correlation between these two variables. As solar radiation increases, the solar panel's power output also increases proportionally, with the data points forming a straight-line pattern upwards. This shows that the amount of sunlight significantly impacts the solar panel's performance, which is what one would anticipate for a photovoltaic solar panel. On the horizontal axis, the solar panel output power reaches a maximum of close to 2.0 kW, corresponding to the nominal capacity of the panel recorded in the system.

Meanwhile, the solar radiation on the vertical axis shows a range of up to 1.4 kW/m², which illustrates the variation in the intensity of sunlight received over time. This correlation confirms that the solar panel is functioning correctly and producing power according to the level of radiation received. Furthermore, there is no significant deviation from this linear pattern, indicating the system's efficiency in converting solar radiation into electrical energy throughout various radiation conditions.

Fig. 9 shows the relationship between Global Solar (expressed in kW/m²) and Total Renewable Power Output (in kW). The plot demonstrates a very distinct linear pattern in which an increase in renewable power output follows an increase in solar radiation intensity (Global Solar). This pattern indicates that solar radiation exposure directly affects the production of renewable energy sources, which aligns with solar panels' behaviour of producing more electricity as exposure to sunlight increases. The graph also shows a very tight data distribution along the trend line, indicating a strong correlation between the two variables. However, a few data points in the upper right corner deviate slightly from the straight line, which may suggest other factors affecting the power output besides solar radiation, such as the operating conditions of the solar panels or other weather factors. This distribution suggests that although solar radiation significantly determines the power output, other variations may affect the measured results. This anomaly may require further analysis to understand the factors influencing the deviation from the linear relationship.

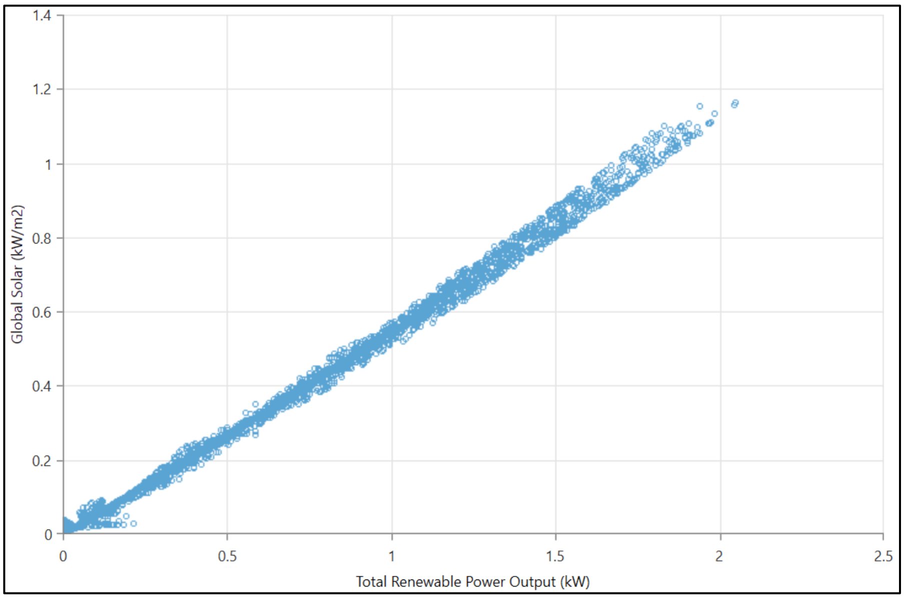

Fig. 9. Global Solar versus Total Renewable Power Output

4. Conclusion

The conclusion of the analysis of the Canadian Solar MaxPower CS6X-325P microgrid system shows that the integration of renewable energy sources with the primary electricity grid can provide a reliable and efficient energy supply. Data and simulation results demonstrate that renewable energy can meet more than 50% of the annual demand, with solar energy penetration peaking during months with higher solar radiation. Energy purchases from the electricity grid balance out the decrease in renewable energy contribution at night or in less-than-ideal weather conditions, ensuring there is never a shortage of energy to meet the load. The PV (photovoltaic) system performs well, with an installed capacity of 2.24 kW and a total annual production of 2,731 kWh, close to the maximum capacity under optimal conditions. Energy is sold back to the grid when energy production exceeds the load, reflecting the microgrid's efficiency in utilising renewable energy. The graph showing the relationship between global solar radiation and PV power output shows a strong linear correlation, indicating that the solar panels work efficiently according to the intensity of radiation received. Overall, the microgrid successfully maximises the use of renewable energy with high efficiency and low energy costs. However, to achieve complete energy independence from renewable energy, it is necessary to increase energy storage capacity or additional renewable resources to reduce dependence on the primary electricity grid, significantly during periods of high load or when solar production decreases. This study shows the great potential of microgrid systems in supporting the transition to clean energy and reducing dependence on conventional energy sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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