Performance Analysis of a Stand-alone Building Integrated Photovoltaic System

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Abstract

This study focus on the performance analysis of a building integrated photovoltaic system for residential energy access. An off-grid 3.8 kWp rooftop PV generator was developed in SolarWatt Park, Alice and was used in the study. Onsite meteorological and electrical data acquisition systems were set up. The parameters monitored are solar radiation, generated PV voltage, current, demand and energy consumption of a house. The results of the study which only involves the PV system performance on March 2019, show a significant amount of solar radiation with total irradiation of 150.72 kWh/m^2, averaging 4.86 kWh/m^2/day. The average PV supply rate was 1.67 kW and cumulative energy of 487.00 kWh, which is equivalent to 15.71 kWh/day. The 3.8 kW 4-plate cooker was observed to be the dominant energy consumer in the house, responsible for 50% of the 10 kWh daily energy consumption. It also generates an average morning and evening peaks demand of 1.18 and 1.32 kW, respectively. Based on the findings, the designed PV system can serve as an alternative energy supply for a single-family house, but the use of an electric cooking appliance is discouraged for effective and efficient utilisation of the system.

Keywords: Energy access, Off-grid, Solar energy, Rural communities, Sustainable development

1. Introduction

Energy supply in South Africa is dominated by non-renewable energy sources with coal-fired power plants responsible for more than 90% and accompanied by nuclear power plants with 6% (Krupa and Burch, 2011; Eskom, 2018; Overen *et al.*, 2018). Energy security of the country is in a critical state due to ageing power plants and the overstrained national grid. Rural communities tend to bear the burden of the derailing energy sector, coupled with weak investment return; most rural settlements are left un-electrified. Moreover, South Africa experiences a considerable about of solar radiation with 2264 kWh/m^2 global horizontal irradiance per annum, equivalent to 6.2 kWh/m^2 daily (SOLARGIS, 2017). In 2010, a pre-feasibility study conducted by Clinton Climate Initiative, contracted by the South African Department of Energy, found that solar power plants can be deployed in South Africa and yield approximately 5 GW over a decade. The findings also indicate that solar power in South Africa can become competitive with coal-fired power, providing clean and secured energy for the country's growing demand (Department of Energy South Africa, 2013).

Based on the findings of the pre-feasibility study, the South African government embarked on a radical and exigent renewable energy practice. The Department of Energy (DoE) and National Treasury entered a memorandum of agreement with the Development Bank of Southern Africa (DBSA) in 2010 to set up the Independent Power Producers Procurement Programme (IPPPP). The office of the IPPPP is mandated to oversee the procurement and monitoring of renewable and non-renewable energy supply to the national grid by private power producers. The renewable energy includes wind, Photovoltaic (PV), Concentrated Solar Power (CSP) and hydro. The DoE set a target of 5 GW generation from renewable energy sources by 2019 and an additional combined 7 GW in 2020. In response to the agenda of the IPPPP, the national utility company set aside 74 GW storage in the national grid for mix energy generation capacity between 2017 and 2027 with renewable energy sources contributing 15 GW (Eskom, 2017).

Renewable energy was also adopted as a strategy to electrify rural communities. In 2011, the DoE adopted the New Household Electrification strategy, which took into consideration that only 90% of households in the country can be connected to the national grid. Alternative energy sources such as solar, wind, biogas or combine (hybrid) will be required to electrify the remaining households. At the end of 2014, 60,000 Solar House Systems (SHSs) were installed nationwide with additional 250,000 SHSs targeted by 2025 (Department of Environmental Affairs, 2016). Singh et al. (2017) designed and implemented a smart embedded rooftop microgrid system. The project which involves approximately 30 households in a rural community in the Western Cape of South Africa was a pilot study aimed to offer insights to the national utility company on the business model of SHSs. The rooftop PV system in the

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project was designed such that participants trade excess energy among each other within the microgrid. The participants were also given the privilege to utilise energy from the national grid when necessary. One of the criteria for participating in the project is that the household should be energy efficient conscious in terms of appliances used. For example, all households were recommended to use a gas cooker and solar water heater (Singh, Olwagen and Moodley, 2019). The iShack SHSs project in the Western Cape of South Africa is a groundbreaking initiative on the electrification of rural/informal settlements. The ongoing project involves the installation of a 50 Wp solar PV power generator in voluntary shacks in a un-electrified informal settlement in Enkanini, Stellenbosch. The PV generator consists of a charge controller, inverter and 12 V 15 Ah battery, sized to provide lighting (CFL), power TV set and charge occupants' mobile phones (Sustainability Institute, 2013; Swilling, 2014; Runsten, Fuso Nerini and Tait, 2018). The Mpfuneko Rural Domestic Biogas project is another non-grid rural energy initiative in South Africa. The project which was initiated in 2013 was designed to construct 55 biogas digesters for cooking for over 200 people in the community. Although the project was funded by the government, the community was made to adopt and own the digesters as households were levied a monthly fee while local organisation collects cow dung, feeds and maintain the digesters (Ierland, 2013).

In accordance with the national imperative of the South African government, a single-family 3.8 kWp PV stand-alone system was designed and developed in SolarWatt Park in Alice, Eastern Cape, South Africa. The project is a pilot study of domestic building integrated PV (BIPV) for mass deployment to surrounding rural communities in Alice. However, this study is focused on the performance of the PV system with respect to local weather conditions; specifically solar radiation, as well as occupant's influence.

2. Description of the site and PV system

Alice is located in latitude 32.8° south and longitude 26.8° east at an altitude of 540 m, Eastern Cape, South Africa. A Google Map of Alice indicating the SolarWatt Park and the house used in the study is given in Figure 1.

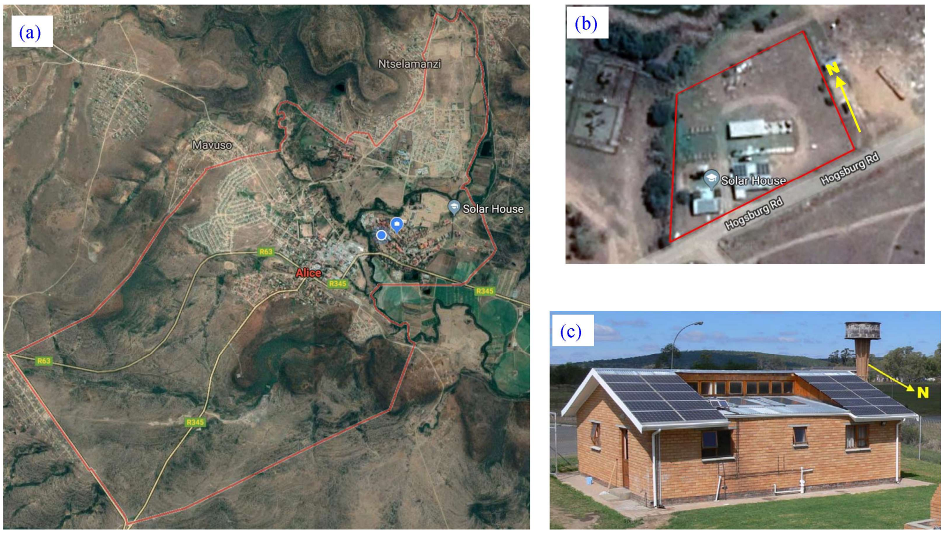

Fig. 1: (a) Google Map of Alice; (b) Google Map of SolarWatt Park; (c) a photo of the house used in the study showing the rooftop PV array

The climate conditions of Alice are characterized with an average dry bulb temperature of 29°C, solar radiation of 606.06 W/m^2 and prevailing east wind in the summer season. A relatively mild winter (no snow) with an average dry bulb temperature of 15°C, solar radiation of 346.17 W/m^2 and westerlies prevailing wind is also experienced (South Africa Weather Service, 2017; Overen and Meyer, 2019).

SolarWatt Park was considered for the design of the BIPV due to its clear north areas with no sun rays' obstacles such as tall trees, mountains and high rise buildings. Hence, the PV array is expected to receive maximum daily solar radiation for optimum power production. As shown in Figure 1 (c), the PV modules were facing geographical north and 20° inclination angle. The selected roof angle is not the optimum angle for PV power plant design but was constrained by the building design. The PV array on the east and west wings of the roof are made up of 20 sets of 190 W PV modules, amounting to a peak power of 3.8 kWp.

The PV modules were accompanied by a FLEX Max 80 MPPT charge controller, Multiplus 48/5000 inverter, and a set of eight 6 V M-Solar 3MIL 25S batteries. Like most MPPT charge controllers, the system's charge controller ensures optimum battery performance over a long period with three fundamental operation mode; Boost, Equalize, Float and Sleep mode. On the other hand, the bidirectional inverter of 38 – 66 VDC input voltage, 230 VAC ± 2% output voltage, 5 kVA and 4 – 4.5 kW output power is used to convert DC power from the charge controller (PV array or battery) to consumable AC power in the house. The battery bank, down the components chain of the PV system, is made up of eight sets of batteries connected in series. Based on the batteries rating, they are capable of delivering 900 Ah with cell voltage above 1.85 V at constant room temperature over 100 hrs discharge period.

3. Research method and instrumentations

A weather station was set up in the SolarWatt Park to continuously monitor the solar radiation, ambient air temperature, relative humidity, wind speed and direction to interrogate the influence of the outdoor ambient weather conditions on the PV system performance. The weather station is presented in Figure 2.

Fig. 2: Setup an outdoor weather station for global horizontal irradiance measurement

However, the measured weather parameters were limited to the solar global horizontal irradiance (GHI) in this study; measured by the Kipp & Zonen CMP 11 pyranometer. As shown in Fig. 2, the CMP 11 pyranometer was mounted horizontally to capture the direct and diffuse radiations which made up the GHI. It should be noted that the GHI is not the exact solar radiation incident on the surface of the PV array. Since the point of array pyranometer in the photo is not on the same angle of inclination with the PV array, the GHI was considered best to describe the influence of solar radiation on the PV performance. The sensitivity of the CMP 11 used in this study is 8 $\mu V/m^{-2}$, a spectral range of 285 to 2800 nm, and a response time of less than 1.7sec (63%) and 5sec (95%) (Kipp & Zonen, 2015). The weather station was elevated by 1 m above the roof, providing unobstructed solar radiation for the radiometers.

The electrical performance measurements of the PV system involving the PV array, charge controller, battery and inverter currents as well as their respective voltages were conducted concurrently with the weather parameters monitoring. Regarding the voltage, the PV and battery voltages were in the same potential with the charge controller input voltage. Likewise, the battery voltage is equivalent to the charge controller output and inverter input voltages. In addition to the current and voltage measurements, the inverter output voltage, power and energy of the PV system, which serves as the house consumption were monitored. All the sensors and devices used in the measurements were connected to a DT80 dataTaker, where data are stored and retrieved periodically. The PV systems electrical parameters data acquisition system are presented in Figure 3

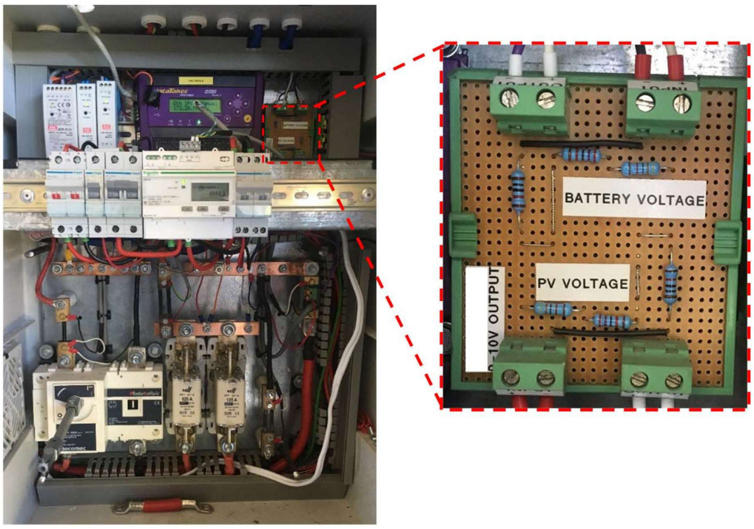

Fig. 3: The PV systems electrical data acquisition system indicating the voltage scaling devices and other measuring instruments

The PV array and batteries currents were measured using 80 A shunt resistors with a voltage drop of 50 mV. The current flowing through the shunt resistor is proportional to the drop voltage, and it is logged using a defined voltage to current multiplier in the DT80 dataTaker. Meanwhile, voltage measurements were not as straight forward as that of current. The DT80 dataTaker is designed to directly measure 30 mV to 30 VDC voltage, whereas full-scale open circuit PV and battery voltages were 120 and 60 V, respectively. Therefore, a voltage scaling device was required to scale-down the PV and battery voltages. As such, an 80 kΩ potential divider network device was used to scale-down the PV and battery voltages. The voltage scaling device in the system was configured to receive 120 V (input) and scale it down to 10 VDC (output) for the dataTaker. It is worth mentioning that the electrical isolation of the input and output voltages of the above various components was not considered in the design of the voltage scaling devices since the DT80 dataTaker is equipped with mechanical relays for this purpose.

4. Results and discussion

The occupants' daily activities with respect to energy consumption were also monitored. It was observed that the house was occupied by a working-class adult male and, his daughter. During the weekdays (Monday to Friday), both occupants were observed to leave home by 08h00 as the father goes to work, and the daughter attends school. The daughter return home by 15h00 and the father by 18h00. On weekends (Saturday and Sunday), they often travel to spend time with other members of the family who live outside town. It was also observed that no mechanical heating or cooling system was used in the house during the monitoring period. In the living room and kitchen, 11 and 14 W CFLs were respectively used. Also, 11 W CFLs were installed in each of the two bedrooms and a 20 W CFL in the bathroom. Some of the appliances used in the house include a 3.8 kW 4-plate cooker, 130 W refrigerator, 70 W TV set and 1 kW microwave oven.

The results in this study only cover the PV performance monitoring in March 2019. To this effect, Figure 4 presents the GHI of the premises over a month and the resultant PV system performance as well as the house demand.

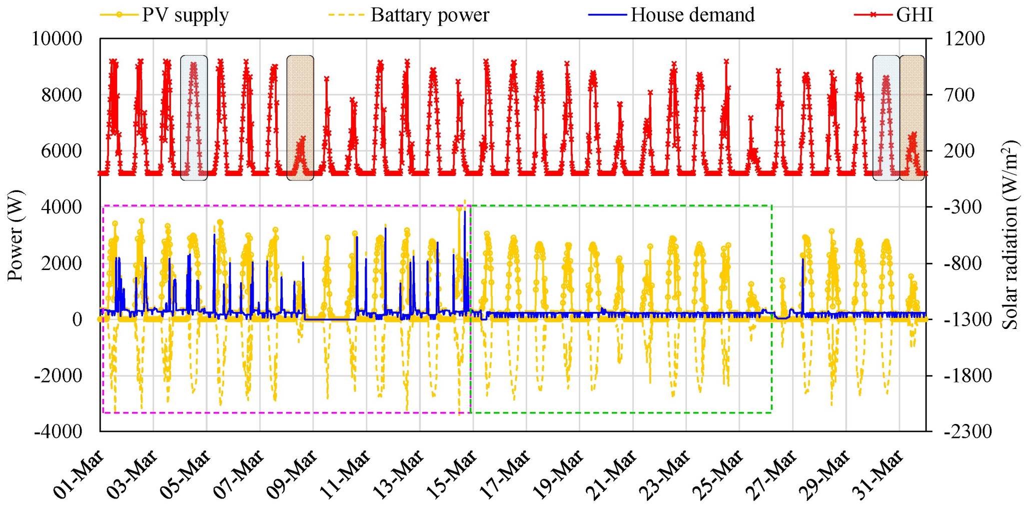

Fig. 4: Performance of the PV system, solar global horizontal irradiance of the SolarWatt Park and the house demand in March 2019.

As seen in Figure 4, a considerable amount of solar radiation with an average of 389.05 W/m^2 between 06h00 and 18h00 daily was obtained on the premises. The PV supply rate as expected, follows the solar radiation trend, generating maximum power during the same period with an average of 1.67 kW. This indicates a close relationship between both parameters. According to the configuration of the data acquisition system, a negative battery power indicates charging, whereas a positive power represents discharging. Therefore, at the early hours (06h00) of the morning, the batteries went into a deep (bulk) charging mode, drawing a large amount of current from the PV array and peaking at mid-day. As a result, the batteries daily power distribution mirrored the PV array supply curve, as shown in Figure 4. Over the monitoring period, the average charging rate of the batteries was 1.32 kW and a discharge rate of 330 W.

The typical morning and evening domestic demand peaks due to cooking and water heating produced the upward peaks in the house demand profile. The downward sequential peaks were generated by the thermostat effect of the refrigerator. With this been said, the house demand profile can be divided into two periods; when electric cooking was performed (01 – 14 March) and period without electric cooking (15 – 26 March). The average demand of house during the former period was 382. 51 W, while the supply rate of the PV array and discharge rate of the batteries at this period were 1.47 kW and 480.07 W, respectively. In the latter period, an average of 204.43 W was demanded by the house with a reduction of the PV supply by 110 W as well as the batteries by 226.28 W. This implies that the house demand and batteries which made-up PV load influences the daily PV supply rate alongside the solar irradiance. Also, the house load determines the discharge rate of the batteries.

Furthermore, the cumulative daily energy generated by the PV array, stored and discharged by the batteries and consumption of the house was evaluated and presented in Figure 5. From Figure 5, the total monthly irradiation was 150.72 kWh/m^2, averaging 4.86 kWh/m^2/day. The corresponding PV energy was 487.00 kWh, which equivalent to 15.71 kWh/day. A total of 369.67 kWh was stored by batteries, but only approximately half of the stored energy was used during the monitoring period. The remaining energy was lost through self-depletion or moved over to the next month. Moreover, the monthly house consumption was 193.11 kWh, i.e. approximately 6.23 kWh/day. The period with electric cooking, resulted in cumulative energy of 109.98 kWh, while period without electric cooking, saw the energy consumption reduced by half; amounting to 57.89 kWh.

Figure 4 was split and grouped into average weekday and weekend profiles under clear and cloudy sky conditions to further analyse the PV system performance with respect to the occupant’s activities and solar radiation. The selection of days based on sky conditions was guided by the measured GHI. In other words, days with regular GHI distribution with peaks greater than 600 W/m^2 was considered as clear sky days, while irregular GHI distribution and peaks lesser than or equal to 600 W/m^2 represent cloudy sky days. Based on the above assumptions, typical clear and cloudy skies GHI of the premises on weekdays and weekends are given in Figure 6.

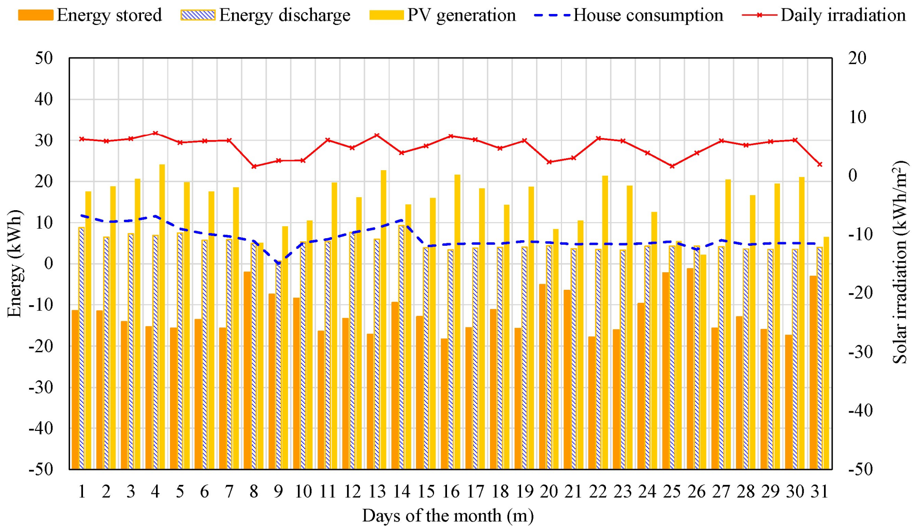

Fig. 5: Daily cumulative energy of the PV array, house consumption, batteries stored and discharge as well as solar irradiation during the monitoring period

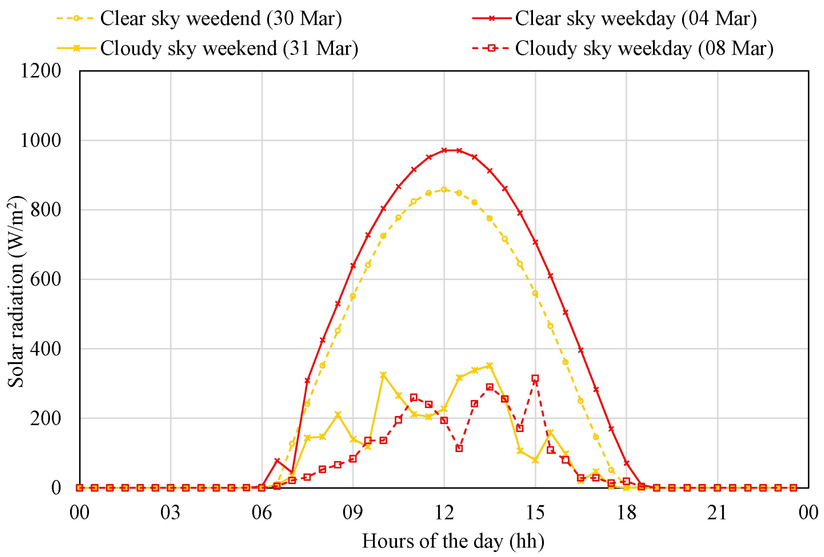

Fig. 6: Clear and cloudy skies GHI of the premises on selected weekdays and weekends

Following the assumptions and Figure 4, 04 March with an average GHI of 557.71 W/m^2, peaked at 12h00 with 971.00 W/m^2 and daily irradiation of 7.25 kWh/m^2 was considered as a clear sky weekday. Clear sky weekend which was represented by 30 March, had an average GHI of 501.99 W/m^2, a maximum of GHI of 858 W/m^2; peaking at the same time and a daily total of 6.00 kWh/m^2. The GHI observed on both cloudy sky days was approximately half as compared to clear sky days. Cloudy sky weekday (08 March) and weekend (31 March) respectively had an average GHI of 123. 59 and 165.8 W/m^2, peaking at 15h00 with 351.30 W/m^2 and 351.60 W/m^2 at 13h00. The total irradiation on the cloudy sky weekday was 1.55 kWh/m^2 while 1.91 kWh/m^2 was observed on a cloudy sky weekend. The PV performance in the above selected days and house demand, as well as energy consumption, are given in Figure 7.

The occupancy of the house on weekdays and weekends is visible in Figures 7 (a) and (d), as only the refrigerator and lights were operational during the weekends. As observed during the monitoring period, the occupants often turn on all lights in the house while away during the weekends for security reasons. The average house demand on both weekends was 207. 17 W. However, with the refrigerator switched on by the thermostat; the average demand was 238.83 W and 86.87 W while it is switched off. The cumulative daily energy on both days was approximately 5kWh.

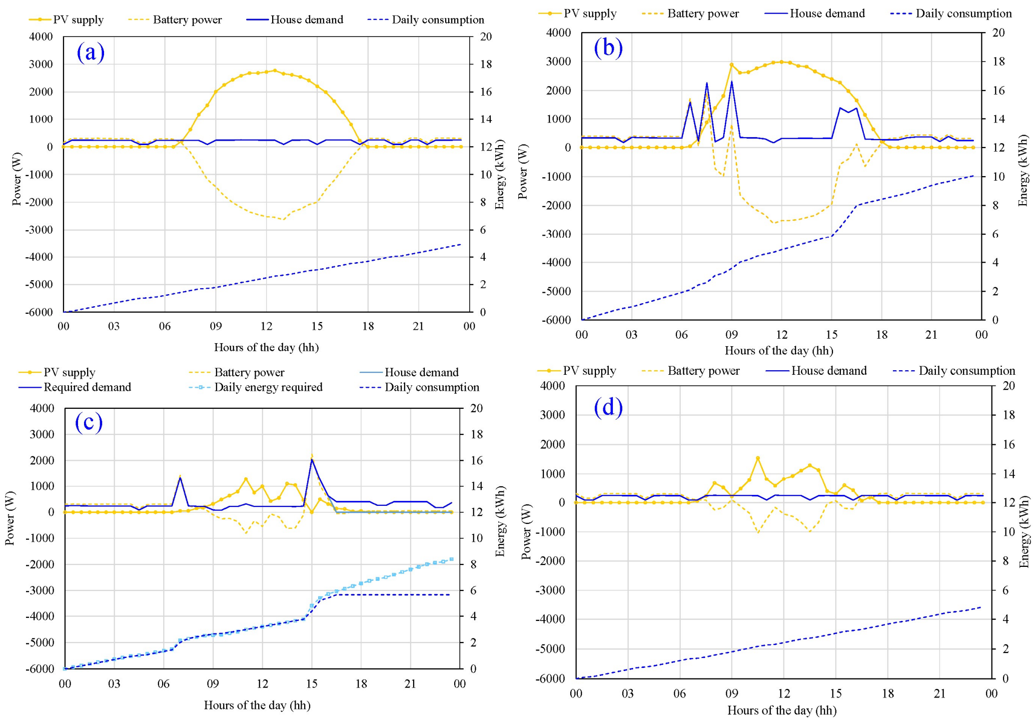

Fig. 7: The PV system performance on a typical; (a) clear sky weekend, (b) clear sky weekday, (c) cloudy sky weekday, and (d) cloudy sky weekend

As indicated earlier, the occupants tend to perform their morning activities between 06h00 and 08h00. By 15h00 to 17h00, the occupants are often indoor after the day's task, preparing for their evening meals. The 3.8 kW 4 plate cooker was observed to be the major contributor of the morning and evening peaks demand. On both days, the average morning peak demand was 1.18 kW and 1.32 kW in the evening, while the whole building daily cumulative energy was 10 kWh.

As seen in Figure 7, the PV system continuously powers the house load irrespective of the sky condition during the weekends, but a different circumstance was observed on the weekdays. On the clear sky weekday, a fairly steady PV supply of 1.93 kW average with a daily generated energy of 24.10 kWh was observed. The house consumed 23%, and the batteries accumulated 62% of the total generated energy. During peak demand periods (morning and evening), the PV supply was, however, not sufficient for the house load as the batteries were found to provide the supplementary supply. The occupants eventually experienced an uninterrupted power supply.

In Figure 7 (c), the PV average supply and daily energy generated were 454.64 W and 5.23 kWh, respectively. The daily energy required in the house, comparing with the house load in Figure 7 (b), was found to be 7% higher than the PV energy generated. As a result, extra power from the batteries was required during both peak demand periods. During the morning peak demand period, the batteries supplied 100% of the 1.14 kWh consumed in the house and 96% of the 1.96 kWh used in the evening peak period. By 16h00, the batteries were fully depleted; leading to the disconnection of the house from the PV system, as shown in Figure 7 (c).

5. Conclusions

In this study, the performance of a domestic building integrated PV (BIPV) was explored. To this effect, the solar global horizontal irradiance (GHI) of the premises was monitored to interrogate the performance of the PV system with respect to the occupants' daily activities. Parameters such as the voltages and currents of the PV array and batteries as well as the demand and energy consumption of the house were monitored continuously. These parameters were used to compute the daily supply and cumulative energy of the PV array and batteries, which represented the PV system performance. The impact of the occupants' activities on the performance of the system was also taking into consideration.

The results of the study which only involves the PV performance on March 2019, show a significant amount of solar radiation with an average of 389.05 W/m^2 and total irradiation was 150.72 kWh/m^2. The average PV supply rate was 1.67 kW and cumulative energy of 487.00 kWh. The 3.8 kW 4 plate cooker was observed to be the dominant energy consumer in the house, responsible for 50% of the 10 kWh daily energy consumption. It also generates an average morning and evening peaks demand of 1.18 kW and 1.32 kW, respectively. The PV system was also found to continuously power the house load irrespective of the sky condition during the weekends. However, on a cloudy weekday, the house load was disconnected from the PV system during the evening demand period due to low battery power.

The findings of the study show that the location of the BIPV provides sufficient solar radiation, but alternative means of cooking is encouraged for effective utilisation of the system. Comparing similar projects (Sustainability Institute, 2013; Singh, Olwagen and Moodley, 2019) conducted in the country, the weekend load demand is often targeted. Therefore, the design system can provide reliable energy access to a single-family house in the surrounding rural communities in Alice.

6. Acknowledgements

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