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Operational Performance of a Solar Battery Backup System in a Small Manufacturing Facility in Ariaria Market Abia State

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Abstract
The research was designed, installed and tested a Solar PV and battery storage system to guarantee a resilient electricity supply to a small-scale industrial facility located in the Ariaria market of Nigeria, which suffers from fluctuating-loads and intermittency of electricity supply that may disrupt the production process. The instantaneous load and daily electrical consumption were statistically documented regarding temporal and energy demand characteristics. PV grid integration, battery state of charge (SOC) profile, back-up energy capacity and system operational efficiency for adequate drive energy supply during power outages, for critical load and manufacturing were evaluated. The instantaneous load aggregation, time-integrated energy consumption, irradiance-dependent PV drive, temperature-dependent PV drive, battery state of charge (SOC), and energy efficiency mathematical models were created. Ten samples of load demanding periods, with varying facility demand, irradiance, battery discharge and failure of the grid for different durations were analysed. It was seen that the variation of the facility load demand profile with different load demands was in the range of 8.2 to 16.0 kW per day, daily energy consumption 58.4 to 111.5 kWh, PV energy generation 4.1 to 7.3 kW under a variation of irradiance 485 to 820 W/m, battery SOC 91.5 to 57.8% and discharge power 3.8 to 7.4 kW respectively. Backup energy supply rose from 7.4 to 30.2 kWh during the failure of the grid ranging from 1.0 to 3.4 hours and highest operational system efficiency was observed during 2.3-h grid failure period, 86.5-91.4%. The study concluded that the intermittency of the load demand and energy supply can be reduced by the use of concurrently distributed renewable energy generation resources, battery-backed productive load facilities, better energy efficient construction, and operation of equipment, and by having resilient electricity infrastructure system for small and medium scale manufacturing energy users.
Keywords: *Solar photovoltaic system, Battery energy storage, Electrical load demand, Manufacturing plant, Grid outage.*

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I. INTRODUCTION

As of now, domestic photovoltaic solar power generation market is gradually becoming competitive, and the selling price is constantly falling; meanwhile, the operating cost of the whole power grid is year by year increased. As a highly productive industry, the manufacturing industry has a high demand for electricity. Manufacturing industry can provide a much-needed power backup source, particularly during a temporary power outage, and reap significant benefits in the process.

The growing dependence of small manufacturing industries on electricity makes the stability and reliability of the power supply essential for a smooth operation of production processes especially in developing countries where power supply may be prone to undercapacity, voltage fluctuations, and disruptions. Therefore, in small enterprises such as in machinery, lighting, ventilation, refrigeration, computers and information processing equipment etc., power failures can have severe consequences in terms of high production line idling losses, high operating costs, poor productivity and damage to electrical equipment. During the time of system collapse or system failure, the customer is denied energy. The power supplier and customers should consider the energy not supplied at the time of system failure as it is essential to understand the financial implication and discomfort this would have created [1]. The prevalence of power outage challenges has compelled businesses in Nigeria to access other forms of energy such as solar PV, which is backed up by energy storage.

Solar Battery Backup System PV, battery, power conditioning and loads are combined so that power is provided when there is a power outage or when the sun's energy is not enough. When solar availability conditions are available, the PV array can satisfy the electrical load for the end use facility and charge the

battery bank (if installed) as a function of the type of system, and amount of available generation. The system can then store energy when there is no solar energy or during times of grid outages, but the amount of stored energy is very sensitive to solar PV generation levels, daily load energy demands, PV efficiencies, inverter efficiencies, generator efficiencies, system losses and charging/discharging times of the battery bank.

Ariaria International Market (AIM), Abia State is an important economic and manufacturing hub, with thousands of small manufacturing enterprises engaged in production and manufacturing activities in fabrication, electrical and electronics manufacturing, furniture manufacturing, footwear manufacturing and metal work as well as commercial processing and other related activities. It is found that those small manufacturing units are mainly using electrical equipments of low or high power demand, which may create problems in operation when the supply of the electrical power does not match the demand. This is one challenge that can be addressed with solar battery backup systems, which lessen the need for conventional backup generators; however, the effectiveness of this system in a small manufacturing unit has not been studied extensively.

The system is evaluated for the operational performance by checking the operation modes that the system can meet the load requirements of the facility. Topics to measure are: Solar energy generation, Battery charge/discharge cycles, System state of charge (SOC), Inverter output, Load energy consumption, System efficiency, Backup time, Renewable energy fraction, System's support for critical production processes during a grid outage. These are indicators that can show the difference between what is running and what should be running.

The purpose of this study is therefore to investigate the working of a solar-battery back up in a small manufacturing plant within the market of Ariaria, Abia state. This research assesses the relationship between supply/demand of electrical energy through solar and storage battery into operation of a backup system in the context of energy management and ascertaining the ability of this system to deliver quality electrical energy in support of manufacturing process. This can offer technical data for optimisation of the system, battery management and deployment of the solar-battery backup in the small-scale manufacturing system.

II. RELATED WORKS

The demand and need to develop knowledge on energy performance, economic feasibility, efficiency improvement and operational reliability have been growing as the operation of solar photovoltaic (PV) systems for commercial and industrial applications has increased significantly. The economic impact of the rooftop PV installation has been studied on an industrial plant, and outcomes of the study were used to show the potential contribution of distributed generation in displacing the conventional sources of electricity supply and thus in influencing the operation costs of the industrial plant. The resulting data is useful for the assessment of PV as a reliable and flexible supply to a manufacturing site for its high and fluctuating demand requirements [2].

The efficiency of the electric conversion of PV strongly depends on the environment and the operation conditions. To obtain the lowest temperature of the PV panel and to improve the electrical performance, a hybrid cooling method has been studied to obtain the thermal behaviour of PV conversion efficiency [3]. Similarly, a control requirement was found to be Maximum power point tracking (MPPT), as the working point of PV array changes with its operating conditions (irradiance and temperature). The indirect adaptive control method has thus been referred to as a technique to enhance the maximum power extraction, in comparison to the traditional power maximization techniques for MPPT [4]. Solar tracking has been investigated through comparison of monitoring dual-axis and fixed PV systems to demonstrate that orientation and tracking of the solar position has the potential to improve collection of available solar energy [5].

Other factors such as economic, spatial and social are also relevant for PV system placement and acceptance. Spatial factors and the local socio-economic context were identified as factors that constrain or promote deployment of PV [6]. Similarly, in African urban informal settlements, the spatial limitations have been demonstrated as a barrier to the uptake of household solar-energy systems, as has the technical potential of the systems, highlighting that take-up does not necessarily imply feasibility [7] and in smaller-scale manufacturing plants, investment capacity, load profile, available space and reliability requirements limit system feasibility.

Another important factor to consider when designing a PV system is economic. The levelized cost of electricity of the solar PV is presented for comparison with other energy generation sources and for long term cost of energy estimation [8]. Additionally, the use of model-reference adaptive control has shown potential to improve the system response to changes in operating conditions if the PV power output is controlled [9] and conventional MPPT techniques have been compared favorably to highlight the need to select the proper control method to maximize use of available PV power [9]. In the same vein, load forecasting increases the power supply chain efficiency and revenues in conventional power generation. This means that the utility must perform the proper load planning to meet customer's requirements for energy [10].

More advanced optical and thermal techniques have enabled PV performance to be further investigated. A potential research area are holographic solar-energy systems, where special attention is paid to optical

elements of solar-energy system processing of solar-energy [11]. Studies of PV thermal performance have shown that the effect of temperature must be considered in PV performance analysis since thermal effects affect the cell operating characteristics [12]. PV-thermal technology has therefore been investigated as a combined electrical-thermal power generation system to give a better overall energy utilization from available solar energy [13].

The other approach to PV-efficiency prediction is based on artificial-intelligence estimation. For example, the use of artificial neural networks (ANN) for PV-panel efficiency estimation with regional operating data suggests the applicability of data-driven methods to capture the PV power production nonlinear dependency upon environmental parameters [14]. Another design parameter that has been investigated for solar capture is the tilt angle of the panels for a solar system optimisation [15].

Economic study of residential PV has also incorporated the concept of incentives and break-even study, and the results show that policies can also affect economic competitiveness and PV deployment [16]. An extensive number of citations, however, in the literature that was reviewed is not directly related to the present research problem. In particular, the implementation of osteoarthritis care and medicine safety studies are not immediately usable because they do not provide technical support to PV generation, battery load, manufacturing loads, and the load of interruption of the grid [17-20] – inclusion in the review only lowers its technical value.

While there is a significant amount of work reported in the literature on PV economics, MPPT, thermal management, solar tracking, PV system efficiency estimation, system optimisation and adoption, less attention has been paid to all of these factors in relation to a specific electrical load demand, the state-of-charge of the PV storage, backup duration and essential manufacturing-load supply in the event of grid failure. This supports the work presented here that analyzes solar PV and battery energy-storage system for the scenario of a changing electricity demand and a changing manufacturing production schedule for a small plant at the Ariaria Market.

III. METHODS

3.1 Materials

Relevant data pertaining to Solar PV and battery storage system to ensure a resilient electricity supply for a small-scale industrial facility were considered in this research for the actualization of a more stable, reliable, and efficient power system.

3.2 Methods

The method assesses the relationship between supply/demand of electrical energy through solar and storage battery into operation of a backup system in the context of energy management and ascertaining the ability of this system to deliver quality electrical energy in support of manufacturing process.

3.2.1 Instantaneous Electrical Load Demand

Total facility demand is represented by the simultaneous active-power requirements of production machines, lighting, ventilation, refrigeration, and auxiliary equipment. This equation establishes the instantaneous electrical loading that the solar-battery system must accommodate during normal manufacturing operation at any instant continuously.

$$P_L(t) = \sum_{i=1}^{n} P_i\,(t) \tag{1}$$

where $P_L(t)$ is total instantaneous facility load power (kW), $P_i(t)$ is power consumed by the i-th electrical load (kW), n is total number of connected electrical loads, and t is operating time (h or s).

3.2.2 Daily Electrical Energy Consumption

Daily energy consumption is obtained by integrating the facility demand over the operating period. This relationship quantifies total electrical energy required by manufacturing activities and provides the fundamental basis for sizing photovoltaic generation, battery storage, and evaluating energy-use patterns accurately.

$$E_L = \int_{t_0}^{t_f} P_L\,(t)\,dt \tag{2}$$

where E_L is total electrical energy consumed (kWh), $P_L(t)$ is instantaneous facility load demand (kW), t_0 is beginning of the operating period (h), and t_f is end of the operating period (h).

3.2.3 Solar Photovoltaic Power Generation

Photovoltaic output is determined from rated array power, actual irradiance, reference irradiance, and temperature correction. The model represents practical solar generation under varying environmental conditions and provides the electrical input available for directly supplying loads or charging the battery effectively.

$$P_{PV}(t) = P_{PV,r}\,\frac{G(t)}{G_r}\,[1 + \gamma(T_c(t) - T_r)] \tag{3}$$

where $P_{PV}(t)$ is instantaneous PV output power (kW), $P_{PV,r}$ is rated PV array power (kW), $G(t)$ is actual solar irradiance (W/m²), G_r is reference irradiance, normally 1000 W/m², γ is PV temperature coefficient of power (1/°C), $T_c(t)$ is PV cell temperature (°C), and T_r is reference cell temperature (°C).

3.2.4 Battery Energy Dynamics

Battery energy changes according to charging and discharging power, efficiency, and elapsed time. This relationship represents storage dynamics and distinguishes energy entering the battery from useful energy delivered during backup operation under changing facility demand conditions under real operating conditions.

$$E_B(t+\Delta t) = E_B(t) + \left[\eta_c P_c(t) - \frac{P_d(t)}{\eta_d}\right]\Delta t \quad (4)$$

where $E_B(t)$ is battery stored energy at time t(kWh), $P_c(t)$ is battery charging power (kW), $P_d(t)$ is battery discharging power (kW), η_c is battery charging efficiency, η_d is battery discharging efficiency, and Δt is simulation time interval (h).

3.2.5 Battery State of Charge

Battery state of charge expresses stored energy relative to usable rated capacity. The equation accounts for charging and discharging efficiencies and constrain storage utilization, thereby providing a direct indicator of available backup energy during utility interruptions and outages available throughout the period.

$$SOC(t) = \frac{E_B(t)}{E_{B,\text{usable}}} \times 100\% \quad (5)$$

where $SOC(t)$ is battery state of charge (%), $E_B(t)$ is instantaneous stored battery energy (kWh), and $E_{B,\text{usable}}$ is usable battery energy capacity (kWh).

3.2.6 Overall Operational Efficiency

Overall operational efficiency compares useful electrical energy delivered to manufacturing loads with the energy supplied by photovoltaic generation and battery charging sources. This metric indicates conversion and storage losses and provides a practical measure of system energy performance during operation.

$$\eta_{\text{sys}} = \frac{E_{\text{load,supplied}}}{E_{PV}+E_{\text{grid}}+E_{\text{aux}}} \times 100\% \quad (6)$$

where η_{sys} is overall system operational efficiency (%), $E_{\text{load,supplied}}$ is useful energy delivered to facility loads (kWh), E_{PV} is PV-generated energy (kWh), E_{grid} is grid energy supplied to the system (kWh), E_{aux} is auxiliary energy input, where applicable (kWh).

The block diagram is that of a hybrid renewable energy and backup power architecture for use in industrial applications. The electricity is generated from a Solar PV Array and controlled by Charge Controller/MPPT to store in a Battery Bank or send ahead. The utility power comes in directly with a connection to the central Hybrid Inverter, as well as a diesel generator. The hybrid inverter combines all these energy inputs to reliably deliver energy to critical facility functions. These specified critical manufacturing loads consist of industrial sewing machine, leather pressing and cutting machines, and essential lighting and ventilation machine as depicted in Figure 1.

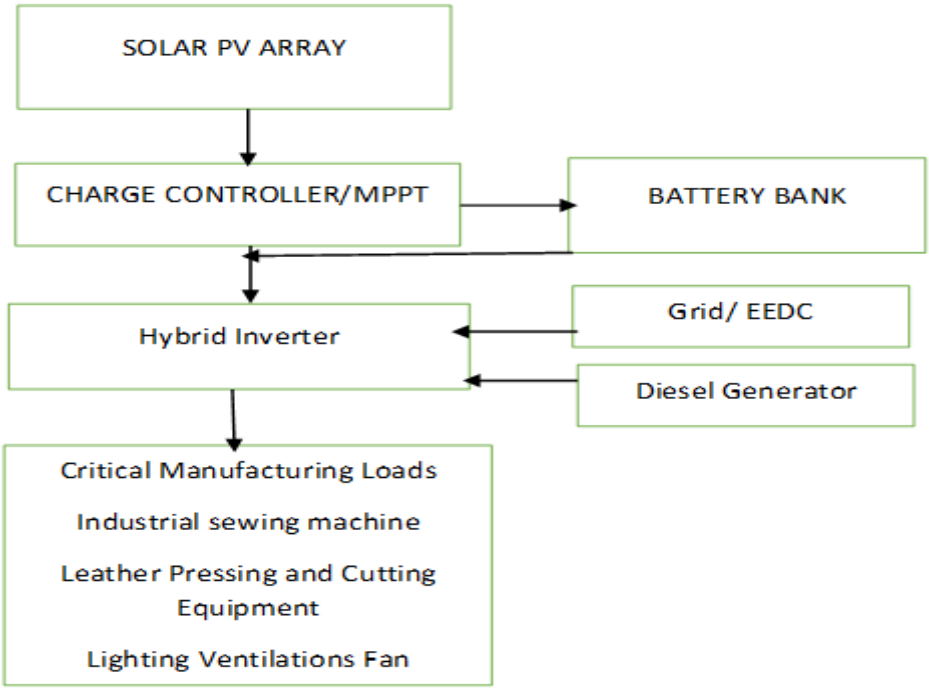


Figure 1: The System Block Diagram

3.2.7 Battery Backup Duration

Backup duration is estimated from usable battery energy and the average critical-load demand. The relationship indicates how long essential manufacturing equipment can remain energized during a grid interruption, subject to battery limits, inverter capacity, and changing load conditions over time.

$$T_{\text{backup}} = \frac{E_{B,\text{usable}}\eta_{\text{inv}}}{P_{\text{critical,avg}}} \quad (7)$$

where T_{backup} is estimated backup duration (h), $E_{B,\text{usable}}$ is usable battery energy capacity (kWh) η_{inv} is inverter efficiency, $P_{\text{critical,avg}}$ is average critical manufacturing load (kW).

3.2.8 Critical Load Supply Ratio

Essential-load supply capability is evaluated using the fraction of critical demand served during grid outages. This indicator identifies whether the backup system maintains manufacturing operations and reveals performance limitations associated with insufficient storage, generation, inverter capacity, or excessive demand conditions.

$$R_{\text{CLS}} = \frac{E_{\text{critical,supplied}}}{E_{\text{critical,demand}}} \times 100\% \quad (8)$$

where R_{CLS} is critical-load supply ratio (%), $E_{\text{critical,supplied}}$ is energy supplied to critical loads during outage (kWh), $E_{\text{critical,demand}}$= total energy demanded by critical loads during outage (kWh).

Table 1: System Parameters

Sample	Load Demand (kW)	Daily Energy Demand (kWh)	Solar Irradiance (W/m²)	PV Output (kW)	Battery SOC (%)	Battery Discharge (kW)	Grid Interruption (h)	Backup Energy Supplied (kWh)	System Efficiency (%)
1	8.2	58.4	485	4.1	91.5	3.8	1	7.4	86.8
2	9.1	63.7	560	4.8	88.7	4.2	1.2	9.1	88.1
3	10.4	71.3	635	5.5	84.2	4.7	1.5	12	89.4
4	11.6	78.5	710	6.2	81.6	5.1	1.8	15.7	90.2
5	12.4	84.9	785	6.9	77.8	5.8	2	18.3	91
6	13.2	91.6	820	7.3	73.5	6.1	2.3	21.5	91.4
7	11.8	82.1	745	6.6	76.9	5.5	1.7	16.9	90.7

8	14.1	97.8	680	6	68.4	6.5	2.6	23.8	89.6
9	15.3	105.2	590	5.2	62.7	7	3	27.1	87.9
10	16	111.5	510	4.5	57.8	7.4	3.4	30.2	86.5

IV. RESULTS AND DISCUSSIONS

4.1 Solar Photovoltaic Generation & Environmental Correlation

From the relationship of environmental conditions and solar photovoltaic performance as shown in Figure 2, the trend is a direct proportionality for all 10 operational samples. For every sample, the solar irradiance is 485 W/m^2 and the output power of the PV is as follows: A PV output power of 4.1 kW is obtained at sample 1. As the environmental conditions become more severe, solar irradiances rise gradually, and at sample 6, where the solar conditions are the most extreme, the PV output power rises to its maximum of 7.3 kW. This maximum value is followed by a gradual decrease in both the solar irradiance and the PV output power to 510 W/m^2 and 4.5 kW respectively at sample 10 due to the changes in atmospheric conditions.

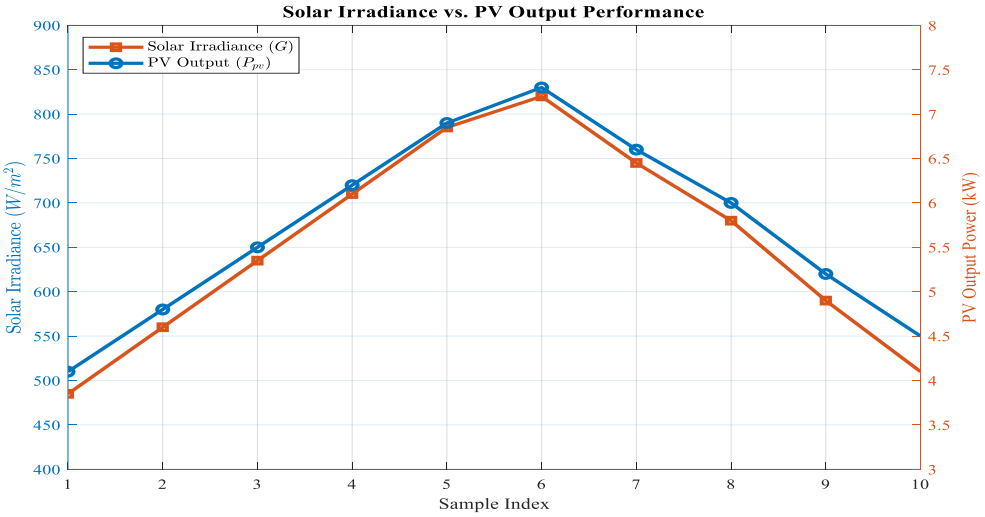


Figure 2: Solar Irradiance vs PV output

4.2 Battery Storage Dynamics & State of Charge (SOC) Trajectory

The dynamics of the energy storage system can be seen in Figure 3, where the battery state of charge decreases with increasing discharge power to meet facility requirements. The battery has a high state of charge (SOC) of 91.5%, and a low discharge power of 3.8 kW in the initial sample. The state of charge of the battery decreases continuously during operation (discharge power increases) and reaches a minimum state of charge (SOC) of 57.8% at sample 10 with a discharge power of 7.4 kW.

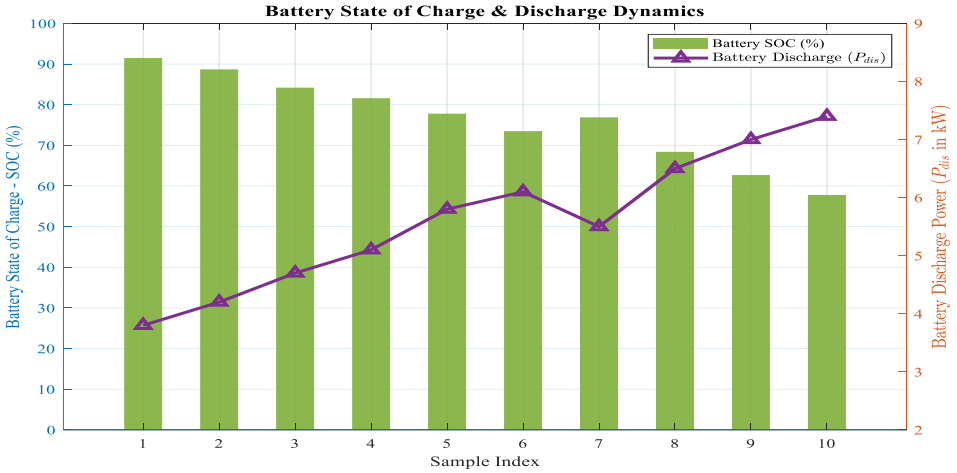


Figure 3: Battery State of Charge and Discharge Dynamics

4.3 Facility Load Demand vs. Daily Energy & Backup Supply

The energy requirements of the facility, along with its backup energy supplies, are explained in Figure 4. The instantaneous load demand increases gradually from sample 1 to sample 10 with values of 8.2 kW to 16.0 kW respectively over the evaluation period, while the daily energy demand increases from 58.4 kWh to 111.5 kWh respectively over the period. The backup energy provided grows proportional to the growing load requirements, rising from 7.4 kWh in sample 1 to 30.2 kWh in sample 10, to support manufacturing when there is an outage.

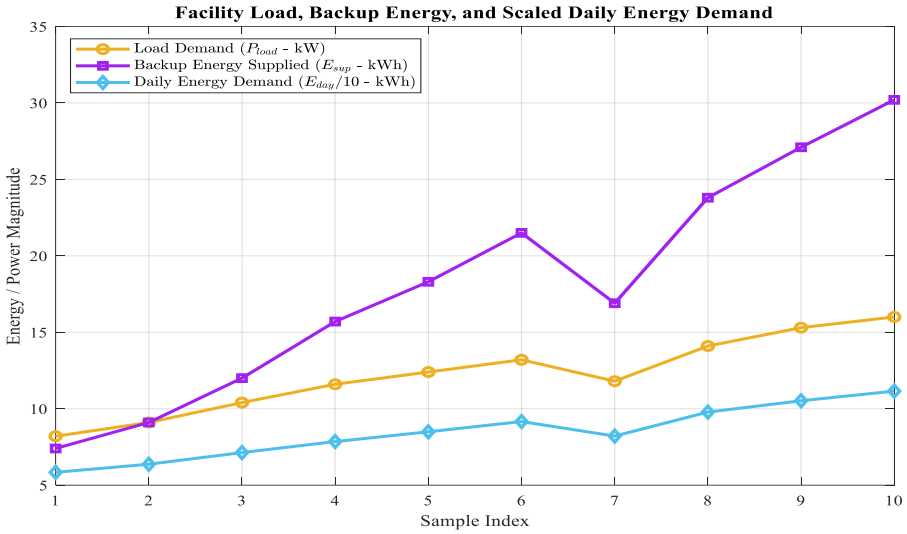


Figure 4: Facility Load, Backup Energy and Scaled Daily Energy Demand

4.4 System Operational Efficiency vs. Grid Interruption

The overall system operational efficiency is shown in figure 5 against different durations of grid interruption. The system efficiency shows a non-linear curve with a rise and then a reduction in efficiency between 1.0 h (sample 1) and 3.4 h (sample 10), during the periods of grid interruption. The efficiency values are calculated starting at 86.8% for a 1.0 h interruption level, peaking at 91.4% for the 2.3 h interruption level and then dropping to 86.5% for a 3.4 h interruption level.

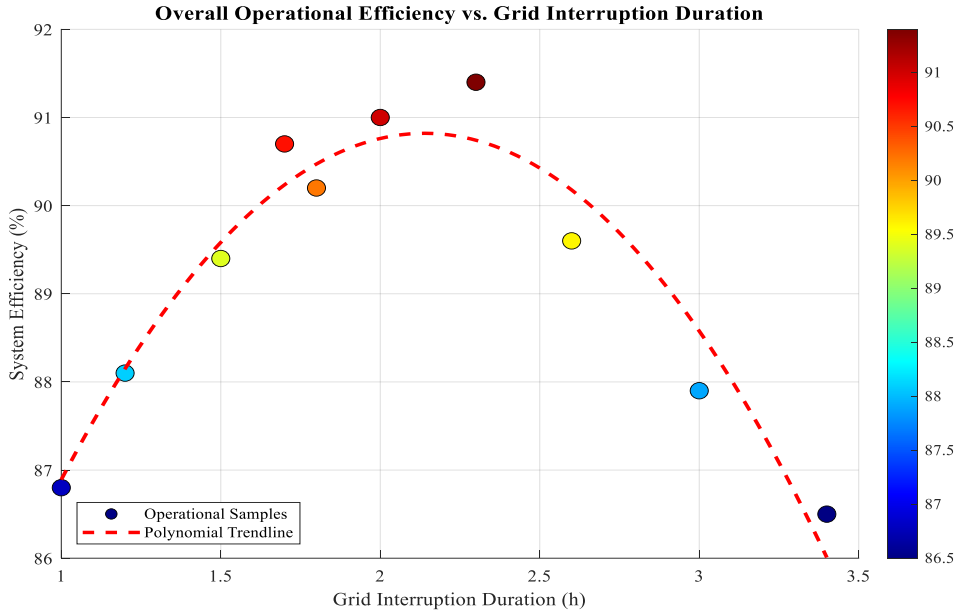


Figure 5: Overall Operational Efficiency

4.5 Multi-Metric Normalized Microgrid Performance Dashboard

The matrix in Figure 6 is a multi-metric normalized performance matrix that collapses all the feedback from the core operational parameters into a single scale ranging from 0 to 1 to give a holistic view of the

microgrid behavior. This detailed comparison plots the normalised load demand, solar irradiance, battery state of charge, system efficiency and duration of interruption to the grid for all ten samples. The visualization is integrated, with generation peaks coinciding with higher solar resource time periods and storage low periods and outages following the loading of the facility and the length of time that the grid is down.

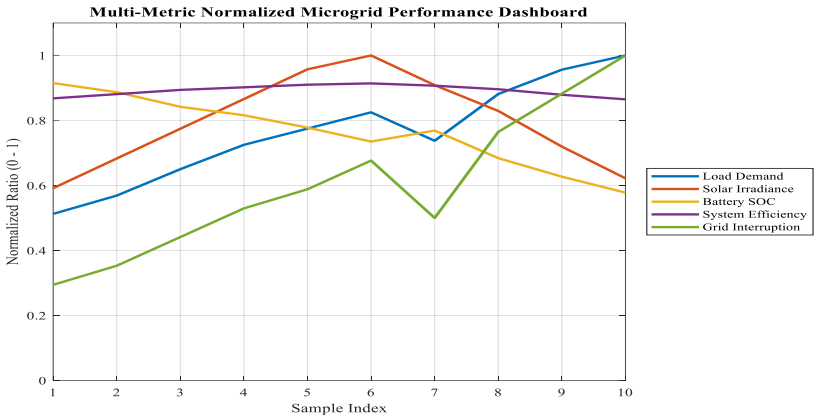


Figure 6: Multi Metric Normalized Microgrid Performance

V. CONCLUSION

The power demand and operational efficiency of PV-battery energy storage system of a small manufacturing unit at Ariaria Market in normal and off-grid operating conditions has been evaluated. The facilities load demand and energy consumption, PV generation, battery behaviour, system operational efficiency and backup capacity were explored. It was shown that the facility load demand rose from 8.2 kW to 16.0 kW, and the daily energy consumption was raised from 58.4 kWh to 111.5 kWh between the 10 samples, due to the different circumstances under which it was operating. The result suggests that the energy demand for manufacturing plants can be significantly influenced by its operation condition and production level.

Therefore, the sizing of PV-battery should be carried out based on the PV-battery representative peak load and daily energy demand of the PV-battery and not the average facility demand. It also demonstrates that the range of solar irradiance from 485 to 820 W/m can produce 4.1-7.3 kW of PV power, and that PV output will increase steadily as solar irradiance increases. The result confirms the PV model adopted has the capability of modelling PV output under varying solar conditions, though the peak PV output remains at 16.0 kW, the peak facility demand, and battery storage and/or grid support would be necessary for exceedance events. The observed battery behavior shows a decrease in SOC from 91.5% to 57.8%, and an increase in discharge power from 3.8 kW to 7.4 kW when the demand increases and the backup time is extended. The discovery also discovered that sufficient usable battery storage capacity and prioritised load consumption are essential to avoiding early battery depletion during the long outage period.

It also illustrates how the supplied backup energy rises from 7.4 kWh to 30.2 kWh and the length of time the grid is interrupted rises from 1.0 h to 3.4 h as demand rises. The proposed PV-battery system can provide backup power for manufacturing companies during power outages, as it has been verified from the result that, if the battery SOC and the facility demand are high, the PV and the efficiency of the inverter are also good, then the PV-battery system can be used. The proposed system achieved the operational efficiency of 86.5-91.4% with 91.4% of the maximum achieved during the grid failure time of 2.3 h. The non-linear behaviour of the system efficiency as the grid time span increases implies that an increase in outage time span would not necessarily proportionately increase the efficiency since its power utilisation behaviour is influenced by battery power conversion efficiency, PV power, demand and operating conditions. The study has showed that PV-battery configuration can be a good alternative to power system enhancement in Nigeria where frequent and long outages are encountered by small manufacturing companies. As well as fostering productive use of electricity, energy efficiency and resilient power systems for SMEs, it can offer a pragmatic basis for implementing and stimulating power distribution to industrial sectors to optimise distributed renewable energy generation. Future work will involve an ageing study of the battery bank, real time prototype testing, cost analysis and permanent load profiling, along with hourly solar resource forecasting and inverter constraints.

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