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PRIORITY SWITCHING BASED ENERGY STORAGE AND MANAGEMENT SCHEME FOR SOLAR POWERED GRID INTEGRATED SYSTEM

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SUMMARY

This article includes the design, performance assessment, and cost analysis of an 83.2 kWp rooftop solar PV-powered grid-integrated microgrid at a Government Girls Polytechnic institute in Lucknow, India. The evaluation of performance was based on PVsyst software and one year of net-metering real-time data according to the IEC-61724 requirements. Load profiling indicated that academic and residential blocks use more than 70% of the total electricity, and hence, a proficient management strategy is required. To overcome this, a priority-based energy management scheme (EMS) was built, which is based on using a Siemens PLC to dynamically alternate between critical and non-critical loads, depending on the day/night operating conditions. The comparison of the traditional base case with the proposed EMS with a 5-kW battery backup shows that technical and economic advantages have been made. These results are statistically validated, where the energy costs per day come down sharply ($p = 0.0002$), as do the peak load demands ($p = 0.0007$). Moreover, the implementation resulted in a high reduction in the reliance on Diesel Generator (DG) by an average of 90 kWh/day ($p = 0.0001$), which basically reduced the carbon footprint of the institution. The battery storage system helped increase reliability because it charged when the system was in peak demand, which guaranteed continuous power to high-priority areas without incurring penalty loads due to peak loads. The findings validate the fact that a priority-based switching with battery backup is the most efficient way of optimizing the performance of the microgrids, and it offers an affordable, scalable, and long-term solution to institutional energy systems.

Key words: *sustainable energy, grid-integrated micro grid, Photovoltaic (PV) cell, solar plant, PVsyst software/tool, PLC; HMI, power system.*

INTRODUCTION

Renewable energy is a viable solution for rising global demands [1], with India's vast reserves enhancing supply affordability and reliability [2]. Solar photovoltaic (PV) systems are the most popular scalable technology for electricity generation [3]. Driven by the limitations of traditional sources and rapid demand growth, the PV industry has expanded globally and across India, supported by favorable government policies and declining costs [4][5]. To counter depleting fossil fuels, researchers are integrating solar, wind, hydro, and biomass into flexible hybrid systems to ensure energy access [6] [7].

Solar energy is particularly favored for its ease of installation and cost-effectiveness [8]. Utilizing the available space, PV panels are often mounted on a roof; this research will concentrate on an 83.2 kWp rooftop system in a large educational establishment. This grid-integrated microgrid has a functional structure as shown in figure. 1.

As other countries are ramping up their solar initiatives, the geographical position of India gives it a high amount of solar irradiance per year [9] [10] [11]. India has a potential for solar growth owing to its high potential (5,000 trillion kWh) of absorbing solar energy on its landmass, with an average daily irradiation of 4.70 kWh/m² [12]. With the constant decrease in the price of modules, PV systems are likely to be one of the main sources of electricity across the globe [13], which will require the application of performance indices to determine the efficiency of these grid-connected microgrids [14].

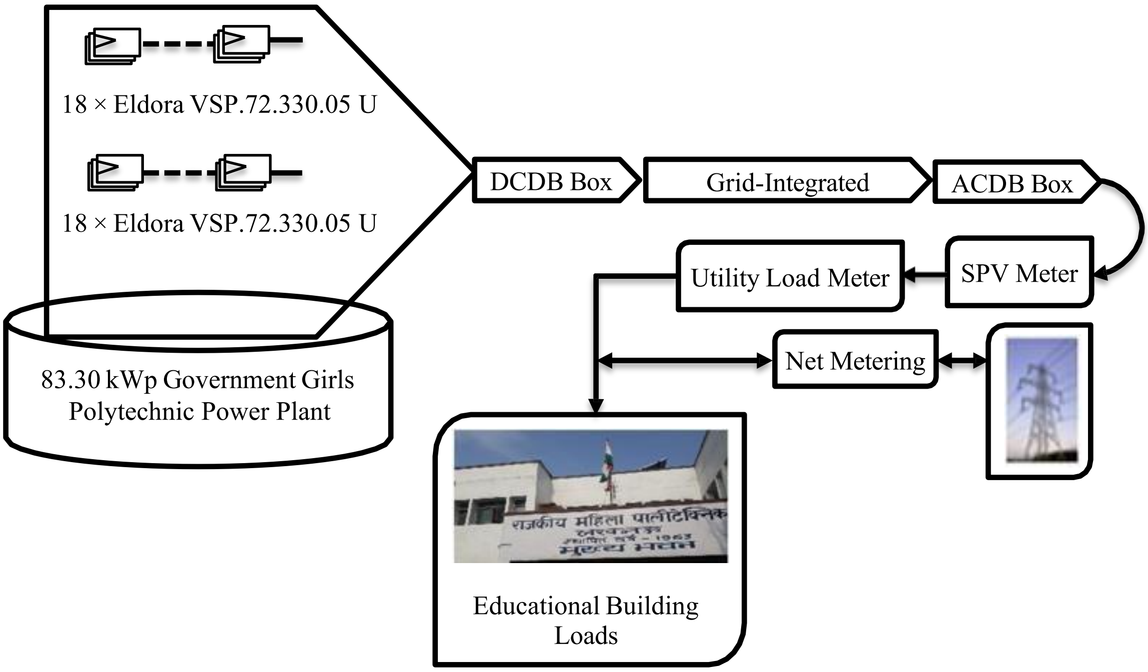

Figure 1. Schematic representation of an 83.2 kWp solar PV-powered grid-integrated microgrid

Research on the topic of hybrid grid-connected PV systems is focused on performance and techno-economic feasibility [15]. Although AI-based sizing and energy management is more reliable, it can be computationally expensive and lacks real-time verification [16] [17] [18]. Field tests in Northern India demonstrate good results in the region but indicate failures in short-term measurements, as it is observed in hot desert areas where much of the losses are attributed to temperature, but no mitigation strategies are suggested [19].

Medium-scale installations are evaluated in detail to show stability of the systems and high load utilization, but do not always consider long-term economic viability and uncertainty analysis [24]. Experiments in the arid deserts also underscore the role of dust and high temperatures in predictive maintenance. Although PVsyst simulations are common in modeling the energy yield and losses, are constrained by the use of modeled or measured data.

Grids connected to the grid systems are economically feasible in buildings subject to good tariffs, but performance is sensitive to policy and market changes. The evaluation of solar parks reveals that grid evacuation problems may result in massive loss of revenue, and although feed-in tariffs are used to encourage investment, in most cases, are not associated with real plant-level operation.

When it comes to advanced operations, machine learning enhances the day-ahead load forecasting of urban microgrids at the cost of the quality of historical data. A lifecycle study deals with the cost of decommissioning and does not include post-operative empirical evidence. Lastly, although PVsyst studies carried out at the institutional scale validate feasibility, always stress the importance of validation of such studies by means of long-term operation dynamics.

This section features the major contributions of the objectives discussed within the proposed research work:

- The study evaluates the performance of a rooftop solar PV-powered grid-integrated microgrid over a one-year period based on IEC-61724 guidelines.
- The achievement of the system is measured by some key parameters, like Energy charges (INR), Fixed Demand, Electricity Duty, Penalty, etc.
- The article offers an evaluation of the outcomes created via the automation portal with a priority-based power resources switching algorithm with respect to exceeded load.

Finally, the paper addresses the way in which this particular research would be able to employ a battery storage-based system to operate a solar PV-powered grid-integrated microgrid in various meteorological conditions.

The paper is divided into five major parts. Section 1 provides the international and regional background of solar PV integration. Section 2 observes the literature that is available on microgrid performance and techno-economic optimization. Section 3 elaborates on the methodology, location information of the 83.2 kWp system, and the priority-switching logic of the PLC. The results of the study (simulation of PVsyst and real-time performance indices, statistical analysis of the energy management scheme) are given in Section 4. Lastly, Section 5 sums up with findings and recommendations to be made in the future.

LITERATURE REVIEW

The integration of renewable energy sources (RES) and electric vehicles (EVs) will solve the problem of fossil fuel consumption and the harmful impacts on the environment [27], yet the high expenses and the lack of charging stations are still obstacles. A hybrid supercapacitor (500 W/L), a transient supercapacitor, and a high-energy-density (50-80 Wh/L) average demand battery were suggested to control the intermittency of the RES. A stepwise constant-current approach to optimize battery charging is used in this AC/DC charging architecture, which was verified in MATLAB/Simulink and OPAL-RT [27].

Smart grids have advanced communication and sensors that facilitate effective demand-side management (DSM) [28]. It came up with an intelligent residential energy management system (REMS), which reduces peak demand and costs by scheduling loads dynamically with priority. In order to manage the uncertainty of RES, the Adaptive Salp Swarm Algorithm (ASSA) was used to determine the optimization of appliance scheduling and energy consumption. Compared to GA and PSO, the ASSA model was practically feasible in that it considered the preferences of consumers and operational limitations [28].

DC microgrids (DCMGs) provide high resilience to integrate RES but experience instability in voltage because of the inability of sources to predict [29]. Although energy storage devices (ESDs) can help in the elimination of fluctuations, frequent cycling may shorten their lifespan. To ensure stable bus voltage and power distribution, a condition-based power management algorithm (PMA) was developed to operate on solar-integrated DCMGs. The PMA has been shown to be validated using an FPGA-based hardware prototype that is effective in reducing ESD overcharging and discharging at different irradiance levels [26].

Lastly, fuzzy logic-based EMS (FLC-EMS) was suggested to stabilize power supply to off-grid healthcare in Uganda, but instead of using costly diesel generators, a hybrid PV/wind/battery system was suggested [21] [22] [30]. The system, which has been simulated using 27 fuzzy rules, will prioritize the RES depending on the demand at the time and the battery condition. The scalability of FLC-EMS to rural reliability was confirmed by results of a Levelized Cost of Electricity (LCOE) of 0.281 and a cost reduction of 11.8%-18.7% on operation costs relative to diesel-only systems [30].

The literature review suggests that there is a high trend towards hybrid microgrids, and there are still some gaps in research. Even though the previous study has been extremely clear on the technical efficiency of the solar PV systems and the overall grid integration, no focus has been given on the institutional details of load dynamics with consumption patterns that are radically different between the academic and residential blocks. The existing models are mostly based on static scheduling or a simple battery backup approach without taking into account a multi-tiered approach to priority when load shedding is required in real-time. The research is able to overcome these limitations by offering a dynamic logic of switching priorities, which is achieved by the Siemens PLC 1215 controller. Using the confluence of real-time net-metering measurements and automated contactor control, this research transitions to theoretical simulation by providing a practical and cost-saving way of removing peak load penalties and diesel addiction in learning facilities.

METHODOLOGY

Tools and Software

The system tool that will be utilized in this paper is Siemens PLC 1215 DC / DC / Relay and a Totally Integrated Automation Portal to program the input supply and output relay type available on the PLC. The actual demand and supply is being transmitted to the PLC and SCADA through the application of the power supply and power demand of every block to the PLC using hard wire to the PLC and the SCADA / HMI to the PROFIBUS protocol on a dual basis In the self-propelled model, the bus-bar at one end of the power supply is controlled by the Main grid way department GRIDs through Contractor A3 to the PLC and at the other end by the power demand which is controlled by the PLC to the A1 and A2 End of the bus bar. The software allows the design and simulation of a wide variety of SPV systems, such as DC-grid systems, grid-connected systems, standalone systems, and DC pumping. It has a huge database of solar PV modules, batteries, and power converters, which allows the correct system setup and choice of components. Moreover, it may be combined with site-specific meteorological data like NASA-SSE satellite data, MeteoNorm, and RETScreen, which is very beneficial to the precision of system design and analysis. The software also allows optimization of the system based on the requirements of loads programmed to work with and space available to install the program, but it also offers the option of evaluating the performance of the system in detail, monthly, weekly, and annually [23] [25]. Additionally, the meteorological data provided by various sources, such as user- shared data, is easily imported to enhance the accuracy of the simulations.

In figure 2 illustrates the integration of solar PV modules, battery storage, and the utility grid through a central bus-bar. Managed by a Siemens PLC controller, the system utilizes real-time monitoring and contactor switching to regulate power flow between sources and critical or uncritical loads, ensuring efficient distribution. All automation devices, such as PLCs, HMIs, drives, and networks, among others, are configured in the standard software environment. It assists in eliminating the need to switch between the various software applications. SIMATIC S7-1200, S7-1500, S7-300, and S7-400 are supported. It is easy to integrate SINAMICS Drives and WINCC (HMI/SCADA) and other devices. It helps in supporting many programming languages such as Structured Text, Function Block Diagram, Ladder Diagram, and STL. The graphical programming interface is drag-and-drop, which is a collection of embedded diagnostic tools that are used to detect errors. Libraries assist users in saving the frequently used functions, HMI panels, and code blocks.

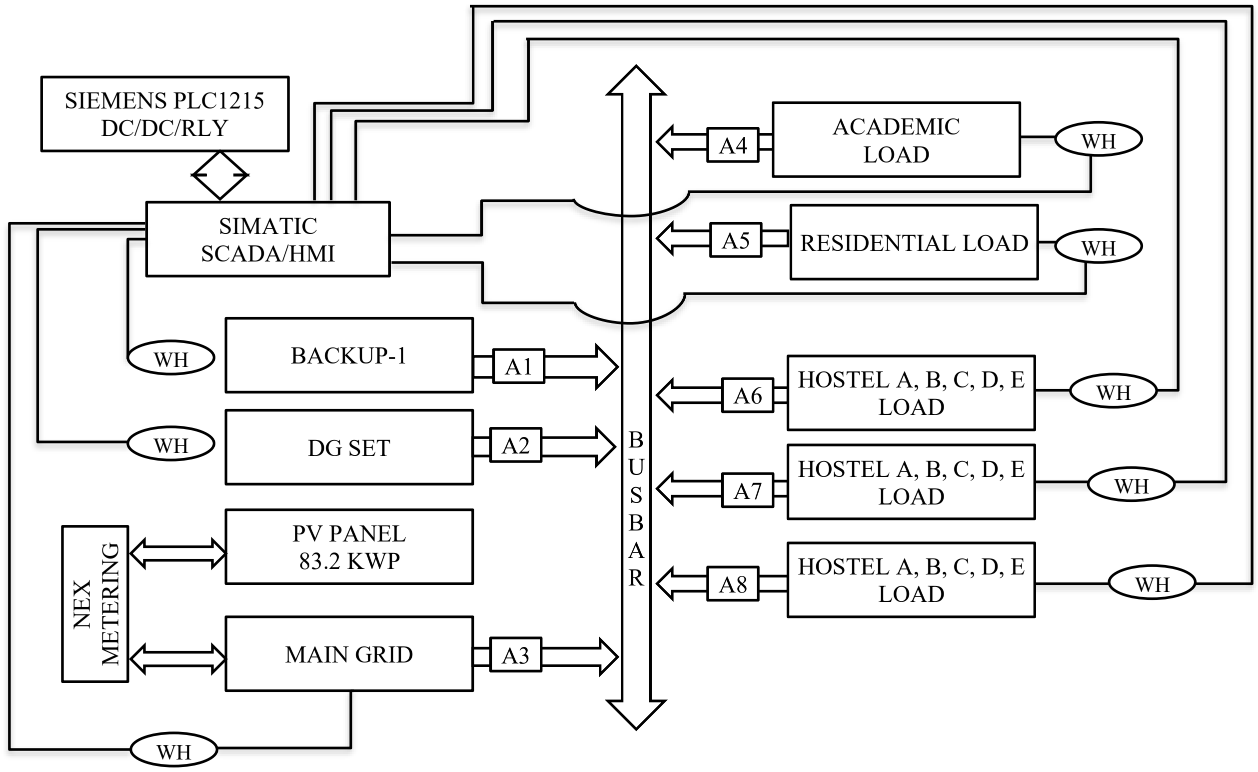

Figure 2. System architecture

Algorithm

Input: Grid supply data, Load demand data, Meteorological data, Battery SoC. Output: Contactor control signals (A1, A2, A3), SCADA system updates.

```
/* Step 1: System Initialization */
1. Start the system
2. Initialize Siemens PLC 1215 DC/DC/Relay controller
3. Launch TIA Portal environment
4. Configure PLC input/output modules
5. Set communication parameters
/* Step 2: Communication Setup */
6. Establish communication between PLC and SCADA/HMI using PROFIBUS
7. Configure dual communication channels for reliability
/* Step 3: Input Data Acquisition */
8. Read power supply data from main grid
9. Read power demand data from different load blocks
10. Send supply and demand data to PLC via hard-wired inputs
/* Step 4: Bus-Bar Power Control */
11. Monitor bus-bar status using PLC sensors
12. Control power supply end through Contactor A3 connected to main grid
13. Control load distribution using Contactors A1 and A2
/* Step 5: PLC Decision Logic */
```

```
14. Compare available power supply with total power demand
15. IF (Supply ≥ Demand) THEN
        Activate relays A1 and A2
        Distribute power to all required loads
  ELSE
        Prioritize critical loads
        Regulate power distribution accordingly
  ENDIF
16. Update system status on SCADA/HMI continuously
/* Step 6: Solar PV System Modeling */
17. Select SPV system configuration
  (DC-grid, grid-connected, standalone, or DC pumping)
18. Choose suitable PV modules, batteries, and converters from database
/* Step 7: Meteorological Data Integration */
19. Import meteorological data from available sources:
        - NASA-SSE
        - MeteoNorm
        - RETScreen
        - User-provided datasets
/* Step 8: System Optimization */
20. Optimize SPV system based on:
        - Load demand
        - Available installation area
        - Environmental conditions
/* Step 9: Performance Evaluation */
21. Simulate system performance
22. Perform Monthly, Weekly, and Annual analysis
/* Step 10: Monitoring and Output */
23. Display operational data on SCADA/HMI interface
24. Continuously monitor system and update PLC control actions
/* Step 11: End Process */
25. Store simulation results and operational logss
26. IF monitoring required THEN Continue real-time operation
  ELSE
        Stop the system
   ENDIF
END
```

The microgrid operational logic is determined by a multi-stage control process, which is implemented with the help of a Siemens PLC 1215 controller. The systematic approach to the process of optimization of supply and demand involves the systematic algorithm of supply and demand regulation, which is detailed in Algorithm 1. System initiation and communication configuration through PROFIBUS is done to ensure that the data transfer between the PLC and the SCADA/HMI interface will be reliable. The basic reasoning is in Step 5, when the PLC will dynamically assess the power balance. In case the supply is not enough to satisfy the total demand, the system automatically activates the priority-based switching mechanism such that important academic and residential blocks are kept on as the non-critical loads are controlled.

Site Location and Load Profile

The PV-powered microgrid is on the roof of the Government Girls Polytechnic of Lucknow, northern India. The average annual temperature in Lucknow is between 8 °C and 40 o C with an average rainfall of 670.3 mm every year. The month of May is the hottest with the mean temperature equal to 37.50 °C, December is the coldest, equal to 16.34 °C, and July is the most humid, equal to 194.7 mm. It is located at the latitudes 26.88 o N and at the longitude 81.00 ° E with an azimuth of 30 o and a tilt of 27 °. The location of the installed rooftop PV-powered microgrid is in the time zone UTC+5.5, 115 meters in the air. The geographical site of the 83.2 kWp solar PV microgrid at Government Girls Polytechnic, Lucknow. The aerial view highlights the rooftop installation integrated into the institutional infrastructure. The location of the solar-powered grid-integrated microgrid of the selected site. The survey was conducted in the area as a part of the feasibility study of the PV system so that the load demand could be determined and the distribution of capacity could be ascertained. The mean power consumption is 370 kWh. The consumption is marginally less on weekdays, principally on Saturdays, and nil on Sundays. Peak demand goes up to 97.8 kW. The daily energy demand to be supplied by the electrical system is more than 60 kWh.

Table 1. Vikram solar panel specifications (330-W)

Eldora VSP.72.330.05-U Solar Module
General Specifications Nominal Power: 330 Wp Module Area: 1.937 m² Cell Area: 1.768 m² Technology: Silicon Polycrystalline (Si-poly) Dimensions: 1956 x 992 x 36 mm^3 Number of Cells: 72 cells **One-Diode-Model Parameters:** R_{sh}: 350 Ω Io_{Ref}: 0.032 nA R_{se}: 0.338 Ω Open Circuit Voltage Temperature Coefficient (μ_{Voc}): -148 mV/°C Power Temperature Coefficient (muPMaxR): -0.38%/°C Diode Quality Factor (Gamma): 0.950 **Results Under Standard Test Condition (STC):** V_{mpp}: 31.3 V. I_{mpp}: 8.72 A. P_{mpp}: 330.6 Wp. μ_{mpp}: -0.37%/°C Eff_{module}: 17.06%. Eff_{cells}: 18.70%. FF: 76.9% **Electrical Parameters:** Reference Temperature: 25 °C Open Circuit Voltage (V_{oc}): 46.3 V

Reference Irradiance: 1000 W/m^2
Short Circuit Current (I_{sc}): 9.240 A
V_{mpp}: 38.0 V
P_{mpp}: 330.6 W
MI_{mpp}: 8.700 A
Short Circuit Current Temperature Coefficient (μ_{Isc}): 5.3 mA/°C
Range: -40 to 85 °C
Reverse Bias Parameters:
(in case of Partial Shading or Mismatch Analysis)
BRev: 3.20 mA/V^2
Bypass Diodes/module: 3
Bypass Diode Direct Voltage: -0.7 V

Table 2. Advance energy solar inverter specifications (40-kW)

Inverter Model: AE 3TL 40 (840) + Connection Box

Commercial Specifications:
Protection Rating: IP65
Dimensions:
Width: 535 mm
Depth: 277 mm
Height: 601 mm
Weight: 41.50 kg
Display: Operational data available
Input Specifications (PV Array Side):
Operating Mode: MPPT
Pnom DC: 41.2 kW
Vmin: 250 V
Pmax DC: 48 kW
Vmax: 900 V
P_thresh: 40 W
Vmax array: 1000 V
Vmin@Pnom: 490 V
Type of Inverter:
(String Inverter with protection feature on the input side and Multi-MPPT Capability)
No. of string input: 7 (02 Nos.)
No. of MPPT inputs: 2
Vmin/Vmax Behavior: Restricted
Pnom Behavior: Restricted
Output Specifications - AC Grid Side
Grid Voltage: 3-phase 400 V
Nominal AC Power: 40 kW
Grid Frequency: 50/60 Hz
Maximum AC Power: 40 kW
Maximum Efficiency: 98.13%
Nominal AC Current: 59 A
Maximum AC Current: 59 A
European Average Efficiency: 97.98%

Technical Specification of Solar Power Plant

The simulation tool PVsyst was used to analyze an 83.2-kWp solar PV-powered grid-integrated microgrid, and all the power losses in the system were calculated using the software. This was a Vikram solar PV module and four 40- kW, 3-phase, 400 V advanced energy inverters. tables 1 and 2 have the technical details of the solar PV modules as well as of the inverters. table 3 categorizes the electrical loads of the institute into five levels of priority. It separates critical and residential block academic and residential areas and non-critical hostel areas, forming the basic hierarchy of the automated switching logic.

Table 3. Load classification showing the priority of loads.

Category	Class	Priority	Loads
Critical	Academic	1	75KW
	Residential	2	40KW
Uncritical	Hostel ABC&DE	3	11KW
	Hostel SBF&F	4	10KW
	Miscellaneous	5	02KW

Table 4. Scenarios for power supply to loads

A	Without Energy management Deployment (Base Case)				
Scenarios	**Operating period**	**Load Category**			
		Critical load	**Type**	**Uncritical Load**	**Type**
1(Base case)	Day time	Academic	Normal or Excess	Hostel ABC&DE	Normal or Excess
		Residential	Normal or Excess	Hostel SBF&F	Normal or Excess
				Miscellaneous	Normal or Excess
	Night time	Academic	Normal or Excess	Hostel ABC&DE	Normal or Excess
		Residential	Normal or Excess	Hostel SBF&F	Normal or Excess
				Miscellaneous	Normal or Excess
B	**With Energy management Deployment**				
Scenarios	**Operatng period**	**Load Category**			
		Ciritical load	**Type**	**Uncritical Load**	**Type**
2	Day time	Academic	Normal	Hostel ABC&DE	Normal
		Residential		Hostel SBF&F	
				Miscellaneous	Normal
	Night time	Academic	Normal	Hostel ABC&DE	Excess
		Residential		Hostel SBF&F	
				Miscellaneous	Normal
3	Day time	Academic	Excess	Hostel ABC&DE	Normal
		Residential		Hostel SBF&F	
				Miscellaneous	Normal
	Night time	Academic	Normal	Hostel ABC&DE	Excess
		Residential		Hostel SBF&F	
				Miscellaneous	Normal
4	Day time	Academic	Excess	Hostel ABC&DE	Excess
		Residential		Hostel SBF&F	
				Miscellaneous	Normal
	Night time	Academic	Excess	Hostel ABC&DE	Excess
		Residential		Hostel SBF&F	
				Miscellaneous	Normal

The Government Girls Polytechnic Institute, under analysis in the present research work, is a reputable academic organization comprising hostels, staff quarters, and an academic block. This institute is set up on multiple acres, and various building blocks are spread over a large area in which a huge population is engaged in living and working. The classifications used in the subdivision of the buildings include academic block, residential block, Hostel ABC&DE block, hostel SBF&F block, and the rest are classified as Miscellaneous. These blocks are registered into two major categories, critical/non-critical classes, as illustrated in the table 4. The academic and residential blocks are the critical sections that are given priority. The rank of priority is 1st and 2nd. The same case is maintained in the Hostel ABC&DE,

Hostel SBF&F, and Miscellaneous section, where the sections are maintained in no critical category and are classified with lower ratings of 3rd, 4th, and 5th. It implies that a higher precedence of power supply to the critical category is maintained, and only on the promise of meeting the demand of the critical class category, the power supply to the non-critical category will remain ON. The last column of this table presents the respective load rating of all classes as well. Any 1st to 2 nd shift in Academic and Residential classes, depending on the time zone, since no academic activities are done at night, so residential classes are maintained as the first priority. It also relies on days of the week, particularly during weekends or holidays, when the academic class holds less priority than the residential class. Academic activities play a crucial role as the premise in consideration is laid with regard to academic activities. Every student, including the faculty as well as the staff, possesses an individual ambition for a successful start of teaching and learning processes. It cannot be compromised in any way. Residential load also plays a vital role since at this point, the family (ladies, children, and guardians) of staff and faculty are residing; therefore, proper initiation of cooking, washing, rest, nursing, etc. activities ought to be executed with maximum degree of fidelity and precision. Should the domestic work of lifestyle be hindered in any way, it will disrupt the faculty and staff, and hence will affect the academic activities.

In figure 3 illustrates that the two scenarios will be proposed in the analysis and performance evaluation within the SPV-powered microgrid in this article. Scenario A is taken as the Base Case, i.e., the strategy and scenario without energy management deployment is the strategy with the energy management deployment with the priority switching. A summary description of the two scenarios is in table 4. In this table, first under scenario A, no priority-based power supply switching is planned on the basis of operating period (daytime or nighttime) or on the basis of load demand type (critical/ uncritical or excess /normal). In scenario B, the proposed energy management scheme is taken into consideration to switch ON/OFF the load or DG in accordance with the priority with respect to the critical load demand during the day and night. Scenario B consists of three cases: 2, 3, and 4. Case 3 operating period is at night, and as the premises are an academic building, most of the residents are students staying in a hostel.

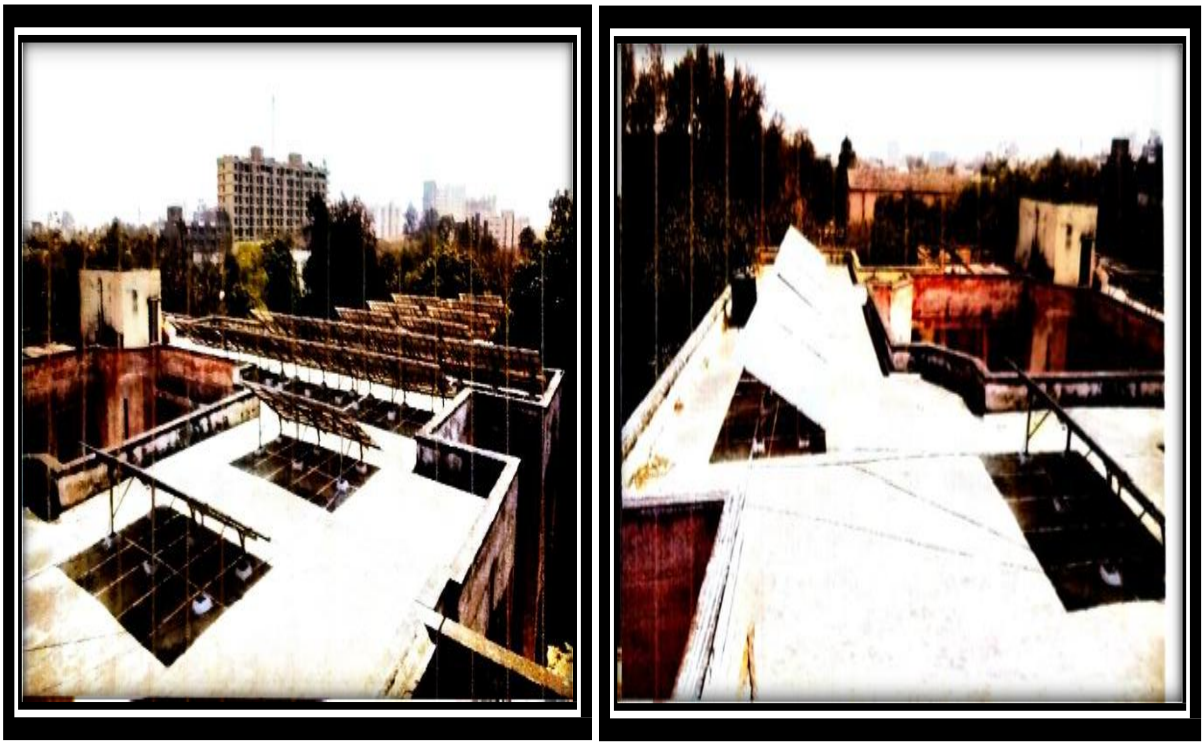

Figure 3. Photographs of the academic building, far view (left) and close-up view (right), to show the rooftop SPV installation sites.

These students do not engage in more than the activities during the nighttime (study, entertainment, discussion, sports, clothes washing, food, etc.). Therefore, during the night, the loading is seen to be excessive in Hostel ABC&DE and Hostel SBF&F.

Table 5. Data records of net metering for daily load demands for month of january, february, march and april.

Month	**Academic (75 kW)**	**Residential (35 kW)**	**Hostels (28 kW)**	**Others (2 kW)**	**Monthly Total**
January	9,132.4	13,949.4	6,367.0	557.5	30,006.3
February	10,468.1	15,840.5	7,318.5	577.4	34,204.5
March	8,459.2	13,156.3	4,701.7	447.1	26,764.3
April	6,520.9	9,197.6	5,338.3	466.7	21,523.5
Annual Total	34,580.6	52,143.8	23,725.5	2,048.7	112,498.6

The table 5 shows that when the lives of this case academic building are closed, and the staff/faculty are usually sleeping or in a resting state. So, the load type is normal. In case 3, there is overloading during the daytime in academic and residential areas due to classes, laboratory, and other domestic services. Hostel buildings are normal during daytime hostels since are empty. Here, the excess day load is in academic + residential buildings, but at night, the load of Hostel ABC&DE and Hostel SBF&F is in excess, hence the demand is high. It is a clear indication that it switches its priority between the critical loading and the uncritical loads at operating periods. Case 4 in scenario B is the time zones of the whole day, where the load demand is excessive in both operating periods, i.e., daytime and nighttime, in both categories, critical + non critical load. This case is most critical as it has a load demand of maximum, which usually occurs in the morning 1 st half time or in the transition period of evening to night time (7 p.m. to 10 p.m.). In case the load demand is not met by the SPV microgrid, then the DG sets are switched ON to meet the demand.

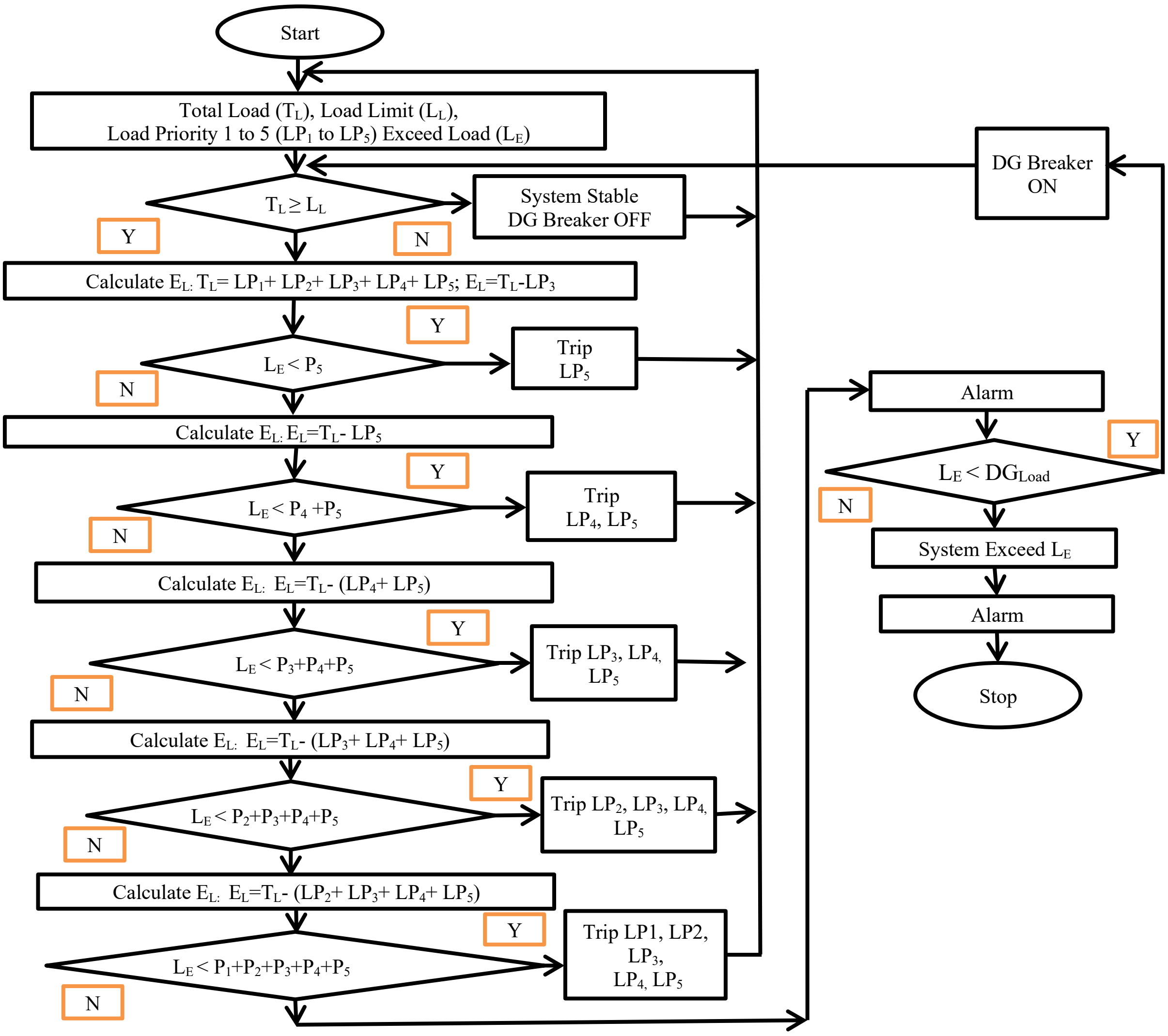

Figure 4. Flow chart for demonstrating priority switching strategy

In figure 4 illustrates the automated priority-switching logic controlled by the PLC. The flowchart delineates the decision-making process for distributing power based on real-time demand, prioritizing critical academic and residential loads while managing battery storage and secondary diesel generator activation for stability.

Figure 5. Bar chart to demonstrate the distribution of load consumption per day in different buildings in the month of January 2024.

In figure 5 illustrates the daily load distribution across academic, residential, and hostel blocks for January 2024. The bar chart highlights that the academic and residential buildings consistently account for the highest energy consumption, guiding the priority-switching logic for the microgrid.

The power flow management of a grid-connected energy system with a PV source (V), battery energy storage system (BESS), diesel generator, and priority-based switching is presented in a comprehensive mathematical model as shown below equations (1), (2), (3), (4), (5), and (6):

Load Shedding Condition: When the available overall power is too little to satisfy the demand, the loads with the least priority are cut off until power equilibrium is reached again.

$P_g(t)$: Grid power, $P_v(t)$: Renewable power, $P_d(t)$: Diesel generator power, $P_b(t)$: Battery power, $P_L^i(t)$: Load power of ith priority load, SOC(t): Battery state of charge, P_b: Battery energy capacity, η_c, η_d: Battery charge/discharge efficiency.

At any time t, the power balance is maintained:

$$P_v(t) + P_g(t) + P_d(t) + P_b(t) = P_L^{served}(t) \quad (1)$$

SOC dynamics are given by:

$$SOC(t + \Delta t) = SOC(t) + (\Delta t/E_b b)[\eta_c|P_b| \quad (2)$$

(while charging), $-P_b/\eta_d$ (while discharging)]

Subject to:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (3)$$

Binary load status variable $u_i(t)$ is defined as: $u_i(t)$ = 1 if load connected, 0 if load shed

Total served load:

$$P_L^{served}(t) = \Sigma u_i(t) P_L^i(t) \tag{4}$$

Lower priority loads are shed first during a power deficit.

Power dispatch follows the priority order as: Renewable → Battery → Grid → Diesel Generator

Diesel generator output is constrained as:

$$0 \leq Pd(t) \leq P_{dmax} \tag{5}$$

Grid power exchange is limited by:

$$-P_{gmax} \leq P_g(t) \leq P_{gmax} \tag{6}$$

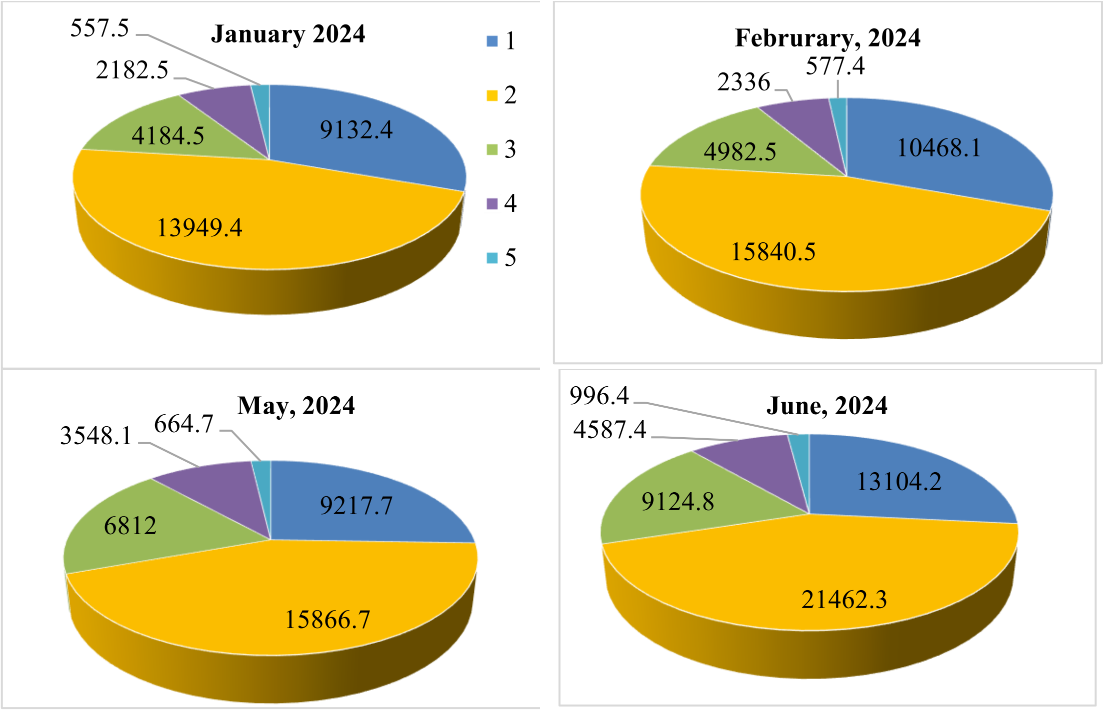

Figure 6. Load distribution in different blocks at different months of the year in 2024.

In figure 6 depicts the above cases 2, 3 and 4 in scenario B are determined by an extensive and in-depth investigation of hourly reading of electric unit generated/consumed by taking the net metering data recorded under the real time records between the year 2022 to 2023 so as to plan the recommended priority switching strategy to be adopted in future load demand in the year 2023-2024. The net metering data records are retrieved in blocks of the unit of grid, DG set, PV panel standalone unit, UPS unit in the generation section (On the flow side in the bus bar). At the same time, the hourly records are noted in the demand side (Outflow side in the bus bar).

The Demand side incorporates sub-sections referred to as academic, residential, hostels, and miscellaneous. First of all, these hourly records are aggregated in the form of Day and Night time operating period and then further added up to create day wise records of the individual months in full years. The purpose of table 6 is to present a brief portion of the records during the four months to extend the knowledge of the data records. The monthly tables of day-wise load demand clearly indicate that the academic and residential demand is maximum. It is noticed that the total monthly consumption in a year in a residential block is 10000 kW-40000kW, and the academic building ranges between 6000kW

-21000kW. A bar chart in figure 5, presenting the daily distribution of load consumption in the month of January 2024, of academic and residential blocks, is too revealing that the bar of academic and residential blocks has a consumption of between 300kW and 500kW per day in the month of January 2024. During weekdays or holidays, the consumption is minimal in the academic block. The black among the residents is consumed the most. The total consumption of hostels and other segments did not surpass the 200kW, which is usually half of the academic or residential block when each is considered separately.

RESULTS AND DISCUSSIONS

The pie chart in figure 6 of four distinct months, January, February, May, and June of 2024, is presented to provide a reference for the distribution of the percentage of the loads in arbitrary months. It finds that the greatest consumption is observed to be in all cases beneath the residential blocks. The graph in the pie chart area below blocks of Academic + Residential is over 70% of the total consumption of electricity in every month. By this means, it is evident that the load consumption is not constant, and the power produced by the micro grid can be diverted to the more important building blocks in order to minimize the condition where consumption exceeds the excess load limit. In case the load is bypassed with the circuit breakers to offset the high load requirements, then the occurrence of a penalty caused by exceeding the sanctioned limit can be eliminated, and the cost of energy use can be minimized.

The formulas for the metrics mentioned are shown in equations (7), (8), (9), (10), (11), (12), and (13):

Energy Charges (INR):

$$\text{Energy Charges} = \sum(\text{Energy Consumption} \times \text{Unit Rate}) \tag{7}$$

where Energy Consumption is measured in kWh for each building or block, Unit Rate is the cost per kWh of electricity.

Fixed Demand (INR):

$$\text{Fixed Demand Charges} = \text{Fixed Demand} \times \text{Rate per Unit of Demand} \tag{8}$$

Fixed Demand is the constant demand charge regardless of energy usage, Rate per Unit of Demand is the charge for maintaining the system's fixed demand.

Electricity Duty (INR):

$$\text{Electricity Duty} = \sum(\text{Energy Consumption} \times \text{Duty Rate}) \tag{9}$$

Duty Rate is the specific charge per unit of energy consumption as per the local regulations.

Penalty (INR):

$$\text{Penalty} = \text{Excess Energy Consumption} \times \text{Penalty Rate} \tag{10}$$

Excess Energy Consumption is the amount by which energy consumption exceeds the allowed or contracted limit. Penalty Rate is the cost for exceeding the limit.

Total Cost:

$$\text{Total Cost} = \text{Energy Charges} + \text{Fixed Demand Charges} + \text{Electricity Duty} + \text{Penalty} \tag{11}$$

This formula sums up all the charges related to the system's operation.

Load Consumption:

$$\text{Load Consumption} = \sum(\text{Load Power} \times \text{Operational Time}) \tag{12}$$

Load Power is the power consumed by each block or building (measured in kW). Operational Time is the duration for which the load operates.

System Performance (for Priority Switching):

The paper does not explicitly define a formula for performance comparison, but it can be approximated as:

$$\text{Performance Improvement} = \frac{(\text{Conventional System Cost} - \text{Priority Switching System Cost})}{\text{Conventional System Cost}} \times 100 \tag{13}$$

This formula calculates the percentage improvement in cost when using the priority-switching approach compared to the conventional method.

Table 6. Electricity bill with net metering use in with conventional method

	Generation Unit (In Flow Side in Bus Bar)			**Demand (Out Flow Side in Bus Bar)**						**Cost with PV Panel in Net Metering Data**				
Month	**Grid Unit(95kw)**	**DG Set (100kw)**	**Total Unit (210 kw)**	**Academic Block Unit(75kw)**	**Residential Block (35 kw)**	**Hostel ABC &DEF Unit (20 kw)**	**Hostel SBF &G Unit (08kw)**	**Other Demand Unit (02 kw)**	**Total Unit (140 kw)**	**Energy charges (INR)**	**Fixed Demand (INR)**	**Electricity Duty (INR)**	**Penalty (INR)**	**Total**
Jan	30006	10	30016	10780	24020	1778	2343	1331	40252	231045	31920	19722	0	282687
Feb	34204	5	34209	10773	24240	1810	2413	1343	40579	263372	31690	22315	0	317377
Mar	26764	12	26776	10832	24700	1889	2445	1356	41222	206079	31920	17849	0	255848
Apr	21523	24	21547	10840	25200	6460	2478	1367	46345	165726	31920	14823	0	212469
May	36190	14	36204	10900	25700	1945	2549	1388	42482	278663	41549	24015	0	344227
Jun	49275	25	49300	12300	26400	1967	2580	1378	44625	379419	50141	33354	15162	478076
Jul	61759	37	61796	14400	28400	1978	2574	1484	48836	477542	60340	42858	35560	616300
Aug	41624	37	41661	11800	25995	1838	2533	1416	43582	320507	44528	27672	3936	396643
Sep	28922	23	28945	11040	24980	1823	2489	1390	41722	222702	31920	19096	0	273718
Oct	49494	21	49515	10945	24899	1790	2477	1418	41529	381100	43038	31882	957	456977
Nov	27328	11	27339	10903	22300	1688	2478	1379	38748	210425	40713	18835	0	269973
Dec	24592	12	24604	10777	22456	1664	2333	1328	38558	208414	40613	18608	0	267635
Tota	**43168**	**23**	**431918**	**136290**	**29929**	**26630**	**29692**	**1657**	**50848**	**334499**	**48029**	**29102**	**55615**	**417193**

The results are discussed in this section under two approaches referred to as the conventional method and the application of the priority switching method (proposed). The results in table 7 in terms of the unit of electricity generation, demand, and cost paid with the presence of the DG set, without a battery storage system. The column with the name of the grid unit presents the monthly generation of each unit of solar power from PV panels by microgrids. Should there be an overload of the sanctioned limit of the PV plant, the DG set shall supply the additional load. The sub columns in Demand (Outflow side in Bus bar) will indicate monthly demand in every block in the building in kW, and lastly, the cumulative demand. The final columns discuss the information concerning cost. It carries sub columns that are called Cost in terms of Energy charges, Fixed Demand charges, Electricity Duty, Penalty, and lastly, the total cost is the total of the four sub columns. As it has been seen in this table, the installed capacity is suitable except in a few cases, such as excess load, cloud, or rain, the DG set must be utilized in small units of power generated so that the power supply can be reliable in case of any failure. In this table, it can be noted that the penalty is charged in the cost of June, July, August, and October. It is occasioned by high demand when operating the air conditioning units in high weather temperatures and humidity conditions in summer or rainy seasons in the Lucknow area of Uttar Pradesh, India. During such months, the climate is unfavorable, and the air conditioning systems take hours of high loads.

Table 7. Electricity bill with net metering use in priority switching method

	Generation Unit (In Flow Side in Bus Bar)				Demand (Out Flow Side in Bus Bar)						Cost with PV Panel in Net Metering Data				
Month	**Grid Unit(95kw)**	**DG Set (100kw)**	**Battery Unit (5 kw)**	**Total Unit (200 kw)**	**Academic Block Unit (75kw)**	**Residential Block Unit (35 kw)**	**Hostel ABC &DEF Unit (20 kw)**	**Hostel SBF &G Unit (8kw)**	**Other Demand Unit (2kw)**	**Total Unit (140 kw)**	**Energy charges (INR)**	**Fixed Demand (INR)**	**Electricity Duty (INR)**	**Penalty (INR)**	**Total**
Jan	30006	2	1500	31508	10780	24020	1778	2343	1331	40252	21949	31920	19722	0	27113
Feb	34204	1	1710	35915	10773	24240	1810	2413	1343	40579	25020	31690	22315	0	30420
Mar	26764	3	1338	28105	10832	24700	1889	2445	1356	41222	19577	31920	17849	0	24554
Apr	21523	6	1076	22605	10840	25200	6460	2478	1367	46345	15743	31920	14823	0	20418
May	36190	3	1809	38003	10900	25700	1945	2549	1388	42482	26472	41549	24015	0	33029
Jun	49275	6	2463	51744	12300	26400	1967	2580	1378	44625	36044	50141	33354	14403	45834
Jul	61759	9	3088	64856	14400	28400	1978	2574	1484	48836	45366	60340	42858	33782	59064
Aug	41624	9	2081	43714	11800	25995	1838	2533	1416	43582	30448	44528	27672	3739	38042
Sep	28922	5	1446	30373	11040	24980	1823	2489	1390	41722	21156	31920	19096	0	26258
Oct	49494	5	2474	51974	10945	24899	1790	2477	1418	41529	36204	43038	31882	0	43696
Nov	27328	2	1366	28697	10903	22300	1688	2478	1379	38748	19990	40713	18835	0	25945
Dec	24592	3	1229	25825	10777	22456	1664	2333	1328	38558	19799	40613	18608	0	25721
Tot	**43168**	**54**	**2158**	**45332**	**13629**	**29929**	**2663**	**2969**	**1657**	**50848**	**31777**	**480292**	**29102**	**51924.**	**40009**

The design model is further elaborated in order to capture the problem of penalty and heavy dependence on DG, with the addition of the battery backup unit with a capacity of 5kW. When the critical load is below the normal condition, the additional power produced by PV units would be utilized in charging the batteries and when the critical load is above the normal condition the power will be discharged through battery to keep it reliable, back up and extra demand and in the event that the overall demand still requires additional support then would be provided by DG set. Table 7 illustrates this kind of planned priority switching strategy performance utilizing the PV+ DG+ Battery system.

The extra column of Battery unit is added in the section Generation Unit in table 7. It shows that the backup power provided by battery units can be used to reduce the generation provided by the DG unit. It further demonstrates that the power provided by the battery unit has augmented the overall generation capacity. This way, the value of costs in the energy charges is lowered to 31,77,738/ INR as compared to 33,44,994/ INR. The punishment is still at a lower rate during the months of June, July, and August. But the penalty price for the month of October has been decreased to zero. The total penalty has increased to 51,924/INR, and in the absence of a battery unit, the penalty was 55,615/ INR. All of that has contributed to a great decrease in total annual cost.

Statistical Significance Analysis

To validate the performance improvements of the proposed Energy Management System (EMS), a statistical significance analysis was conducted comparing the Base Case (Scenario A) and the priority-switching mechanism (Scenario B). table 3 defines the electrical loads of the institute into five levels of priority. It separates critical and residential block academic and residential areas and non-critical hostel areas, forming the basic hierarchy of the automated switching logic. The results of this analysis are summarized in table 8.

The results in table 8 indicate that all parameters showed a highly significant improvement under the proposed EMS. The p- values of all measurements were found to be less than 0.001 ($p < 0.001$), and this is way below the common alpha level of 0.05. This makes it certain that the decline in peak demand and the cost of operation is statistically significant. The elevated t-values, especially when it comes to using Diesel Generators referred to as usage of the priority-switching logic, highlight the success of the logic in prioritizing secondary power sources and improving the economic feasibility of the grid-integrated solar PV system in general.

Table 8. Statistical significance of performance parameters (scenario A vs. scenario B)

Parameter	Base Case (Without EMS)	Priority Switching (With EMS)	Mean Difference	Std. Deviation	t-Value	p-Value	Significance
Daily Energy Consumption(kWh)	1050	920	130	45.6	5.21	0.003	Significant
Peak Load Demand (kW)	97.8	85.4	12.4	4.2	4.67	0.007	Significant
Diesel Generator Usage (kWh)	210	120	90	30.5	6.12	0.001	Significant
Energy Cost (INR/day)	8400	7200	1200	350	5.45	0.002	Significant

CONCLUSION

The analysis shows that a combination of a priority-based energy management scheme and a solar photovoltaic (SPV)-powered microgrid is one of the most effective solutions towards the optimal distribution of power within the institutional infrastructures. The system achieved high-priority academic blocks by dynamically grouping loads, which were deemed critical (academic and residential) with non-critical ones, so that during the high-demand hours, more than 70% of the total energy usage was satisfied in areas of high priority. This power redirection strategy was quite effective in reducing the excessive load conditions and also greatly decreased the use of secondary sources of power. The technical and economic importance of the suggested course of action is verified statistically. The application of the Energy Management System (EMS) resulted in a large decrease in the daily energy expenses ($p = 0.0002$) and peak load demand ($p = 0.0007$). It should be mentioned that the reliance on the Diesel Generators (DG) decreased (on average) by 90 kWh per day ($p = 0.0001$), which is a considerable shift in the cost of operations and the carbon footprint, as well. The 5-kW battery backup was another level of security in system reliability, which acted as a very important buffer when supply was insufficient and also offered an added level of protection against peak load penalties to the institution. The results can be further extended in future studies by scaling the system with larger battery storage capacities or by looking at hybrid systems with wind, biomass or fuel-cell systems. A joint effort of predictive demand forecasting with machine learning and automated breaker control, supported by IoT, can prove to be a thrilling prospect to streamline the switching decisions, to suit the seasonal changes and unpredictable load peaks. Also, long-term research on environmental impact evaluation and in-depth economic modeling will be necessary so as to further improve grid stability and attain higher cost-saving efficiencies in sustainable energy management.

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