A community scale hybrid renewable energy system for sustainable power supply during load shedding

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ABSTRACT

Load shedding is an operating condition in which the electrical grid is temporarily disconnected from the load. The objective is to minimize the gap between available generation capacity and load demand while maintaining an equitable supply for all consumers. Load shedding is a prominent problem for many developing countries. To address this issue, this paper explores the potential of a hybrid energy system (HES) to provide uninterrupted power supply at the distribution feeder despite load shedding from electrical grid. The proposed HES in this work combines photovoltaic (PV) array, battery storage system (BSS) and diesel generator (DG). The HES is equipped with energy management scheme (EMS) that ensures continuous power supply, improves energy efficiency, and minimizes the electricity cost. To accomplish these tasks, the EMS operates the system in one of three modes: grid mode, renewable energy source mode and the diesel generator mode. Besides, the proposed methodology allows injecting surplus PV energy into the grid, thus maximizing PV utilization and improving power system's reliability. The results of this study will assist policymakers to determine the prospect of renewable based hybrid system to supply sustainable power and eliminate the energy problems in the power deficit countries.

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1. INTRODUCTION

The power supply availability-which can be loosely defined as the uninterrupted access to electricity for consumers, is regarded as the basic need of the modern world. However, for many developing countries, the energy deficit is a serious problem due to various reasons such as lack of generation, inefficient transmission network and outdated distribution equipment [1]. In addition, the increasing demand for electricity due to rapid population growth and technological advancements add further stress on the power system. Unfortunately, there is no immediate solution in the near future because the gap between power demand and supply is widening every year. One of the most effective short-term measures to alleviate this problem is to impose load shedding-a scheduled operating condition in which the grid is disconnected from users in a certain area for a number of hours each day. In essence, it removes or curtail specific amount of load when the demand for electricity surpasses its network capacity [2]. Although this constraint is undesirable, load shedding becomes necessary to avert systematic power failure, which can be detrimental to the transmission and distribution infrastructures [3]. On the customer side, the lack of reliable electricity has necessitated the need to opt for self-power generation in the affected countries. The installation of standby diesel generators and the conventional battery-inverter system are the predominant solutions to fulfil the power demands during the intervals of grid outage [2]. Nevertheless, these solutions have their own disadvantages. The widespread adoption of the diesel generators poses both health and the environmental risks while the inefficient battery inverter system can waste 25% or more grid power during the charging and discharging process [4].

Given the ample availability of solar radiation in most of the developing countries, solar photovoltaic (PV) system presents more viable substitution for the conventional sources. However, the common drawback with solar energy is its unpredictable nature. The intermittent of the sun results in variable power generation and thus affects PV system reliability. The hybrid energy system (HES) with more than one energy sources overcomes this drawback of being unpredictable in nature. The HES combines energy sources from both renewables (PV, wind) and non-renewables (diesel generators) depending on the localized conditions [5]. Invariably, the energy storage is also included to optimize the performance of HES [6]. The major characteristic of HES is to capitalize the strengths of different sources and to obtain efficiencies higher than that could be obtained from a single power source. In literature, HES have been used for various applications such as peak shaving [7], base-load power reduction [8], improving power quality [9], as well as cooling and heating provisions [10]. Notwithstanding the number of research works on HES associated with the grid, the question of load shedding was not addressed exclusively as the grid was assumed to be reliable which always supported the power balance of the system [11]–[13]. In case of load shedding, however, these systems will become vulnerable due to frequent disruptions of grid power supply and thus cannot sustain the load demand during abnormal weather conditions.

Considering the limitation of the existing studies, this paper presents a different challenge for HES in urban application to address grid intermittency problem. Furthermore, it addresses the persistent challenge to make HES financially accessible on a community level given the initial high capital cost of the system. By enabling the use of solar PV systems for electricity generation in energy-deficient communities, the proposed methodology reduces the use of diesel generators, thus minimizing the electricity cost for the users. The HES is composed of PV, BSS and DG and equipped with EMS that optimizes the overall performance of the system. The EMS proposed in this study stands out from previous works, as it utilizes HES in conjunction with the grid and not just as a backup system. Besides PV, utility grid also charges BSS under the influence of time of use (TOU) tariff structure during off peak hours only. In case of surplus PV power, it is injected to the grid to achieve the economic benefits of PV energy at any stage. Pakistan is taken as a case study because it faces severe energy crisis since 2008. Currently, the power shortfall in Pakistan is estimated from 3-5 GW [14]. As a result, the country is facing daily power outages for several hours. In spite of the government's attempts to boost net generation capacity using traditional means, the demand-supply balance could not be achieved. The energy problem is becoming worse due to lack of integrated and comprehensive power strategy. Alternatively, Pakistan experiences tremendous potential of irradiance levels all year around. Overall, global horizontal irradiance (GHI) averages 2071 kWh/m² [15]. In southwestern region of Pakistan, about 45-83 MW power can be generated in 100 m² area on monthly basis. While 90% of country area receives higher irradiance levels of up to 1,500 kWh/m² [16]. This existing energy crisis and Pakistan's solar potential provide an ideal scenario to analyze application of HES for sustainable power development. It is worth noting that the proposed model is generic and applicable to any energy poor yet renewables rich countries. Next sections of the paper examine three key aspects. First, a case study is used to describe the localized load shedding conditions and the solar potential of the studied site. Then HES components modelling and rule-based EMS are presented. Lastly, illustrations of HES performance in various load shedding scenarios and weather conditions are given.

2. CASE STUDY: LOCATION

The effectiveness and the applicability of HES is assessed for a residential community in Quetta, a city located in southwestern part in Pakistan. The case study site is situated at 30.1798° north latitude and 6.9750° east longitude, as shown in Figure 1, which illustrates the solar radiation map of the region. It is evident that Quetta has high level of solar irradiance besides having the moderate temperature, making it a promising choice to address the power shortfall in the region. On the other hand, due to inadequate generation capacity, frequent power outages are prevalent in the entire Balochistan state including study site Quetta. This results in an hourly load shedding schedule. The load shedding behavior and the utility supply can be represented as a unit step function [4]. Figure 2 displays the power supply schedule for a specific summer day (14^{th} June 2020) on local distribution feeder in Quetta city [17]. The x-axis denotes the duration of grid outages where the off states correspond to the load shedding periods. On this specific day, load shedding occurs for three separate periods i.e., during hours 6-8, 13-15, and 17-18. It should however be noted that the load shedding schedule varies throughout the year, with an average of 6-7 hours of scheduled outages per day.

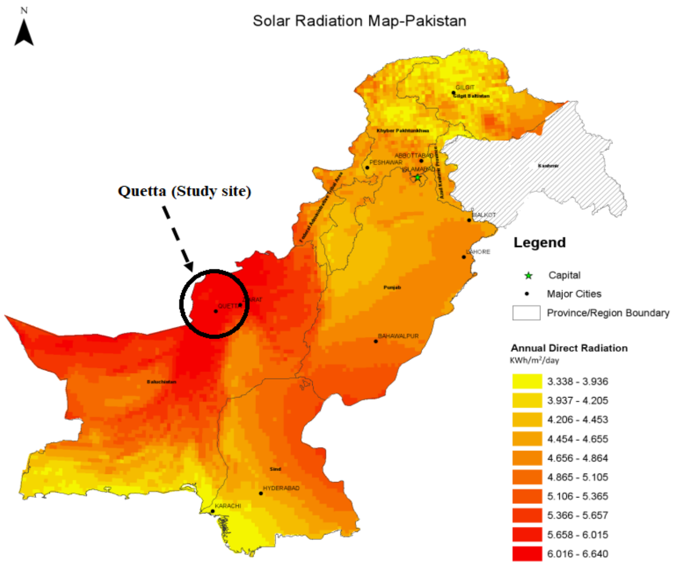

Figure 1. Specific location on country’s map

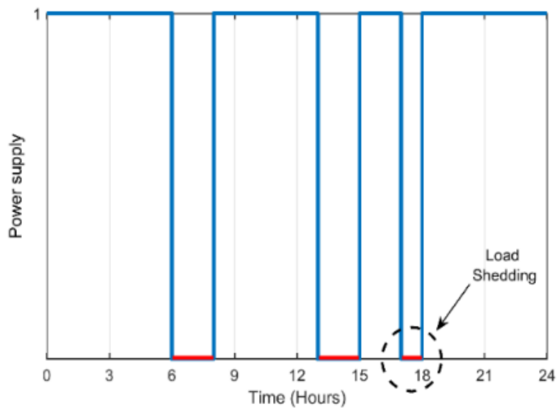

Figure 2. Pattern of utility grid power supply and load shedding of a typical summer day

3. RESEARCH METHOD

To accomplish this research, the proposed HES consisting of PV, BSS and a DG is shown in Figure 3. PV system serves as the primary energy source while BSS and DG serve as the secondary sources to supply the power deficit and transient load demands. The community scale HES is linked to the grid at the distribution feeder. PV arrays and battery storage are connected to the DC bus using power converters. The PV system’s DC/DC converter controls the maximum power point tracking (MPPT), while the BSS’s bi-directional charger manages the flow of DC power in both directions. To store surplus power, Lithium-ion (Li-ion) batteries are proposed due to their higher energy density, efficiency, and longer lifespan [11]. The AC bus connects the community load, diesel generator and utility grid. The AC and DC sources are integrated through one bidirectional inverter to reduce HES’s initial cost. The central controller embedded with proposed EMS will maintain the balance of power by taking into account the operational limitations of each source. Power flow is represented by solid black arrows, while information flow is represented by red dotted arrows between sources and the controller. The HES is expected to provide uninterrupted and economical power supply to load during load shedding, regardless of varying weather conditions. Technical parameters of the HES components are detailed in Table 1.

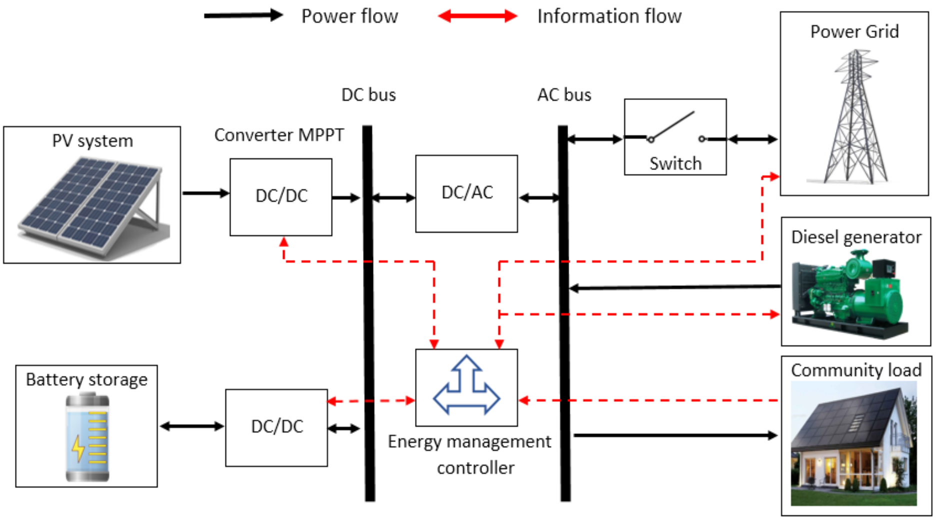

Figure 3. Proposed grid connected HES model

Table 1. Input parameters of HES components

Component	Parameter	Values	Unit
PV	Nominal power	325	Watt
	Efficiency	17	%
	Performance ratio	0.75	-
Battery storage	Nominal capacity	1.8	kWh
	Efficiency	100	%
Inverter	Nominal capacity	30	kW
	Efficiency	95	%
Diesel generator	Rated power	30	kW
	Efficiency	85	%

3.1. Modelling of components

To realize the concept of HES, modelling of system components is performed. Different components modelled are PV, State of charge (SOC) estimation for BSS, inverter, diesel generator and intermittent grid. Once the components of the model are created individually, they can be integrated into the main model of HES. The overall model of HES can then be used to simulate the behavior of the system under different conditions, and to optimize the performance of the HES.

3.1.1. PV model

The single diode model is a mathematical model used to estimate the output power of PV array [18]. It is based on the principle that a PV cell can be modeled as a current source in parallel with a diode. The model considers various factors that affect the electrical output of the cell or module, including irradiance (W/m^2), temperature (°C) and other module parameters at standard test conditions (STC). Using these inputs, the single diode model can calculate the output power of the PV cell or module. The model is used in conjunction with the current-voltage (I-V) curve of the cell or module to estimate its performance under varying conditions. In (1) is used to calculate the output current of the PV module according to this model, while (2) estimates the output power.

$$I_{PV} = [(I_{SC-STC} + k_i(T - T_{STC}))\frac{G}{G_{STC}} - I_0\ [(e)^{\left(\frac{V_{PV}+I_{PV}R_S}{V_T}\right)} - 1] - (\frac{V_{PV}+I_{PV}R_S}{R_P}) \qquad (1)$$

$$PV\_Power = \max\ (V_{PV} \times I_{PV}) \qquad (2)$$

The detail of the variables involved in the (1) and (2) can be accessed in [19]. Using single diode model and the available data, the hourly output power of the PV system is estimated. The hourly weather data (temperature and irradiance) of the studied location is sourced from [20] while other relevant PV parameters are obtained from [21].

3.1.2. State of charge model

Batteries are essential components of HES as they help to store excess energy generated by the PV system or from the grid during times when electricity demand is low. The stored energy can then be used when demand increases, during periods when there is no sunlight or when the grid is unavailable. The absence of grid power happens when the load shedding is scheduled. Charging and discharging process of BSS depends heavily on SOC, therefore estimating SOC is very crucial for successful operation of BSS. To perform this, the ampere hour counting method is utilized as proposed in [22].

$$SOC(t) = SOC(t-1) \times \left(1 - \delta_{bat}(t)\right)\left(\frac{P_{BSS}(t)}{V_{bus}}\right) \times \eta_{bat} \times \Delta t \tag{3}$$

The information about the variables of (3) are provided in [23]. To highlight, $P_{BSS}(t)$ is BSS power during charging and discharging operation based on the available and required power. The required BSS power represents the amount of power needed to reach upper level of SOC (*i.e.*, SOCU) from the existing level. It is denoted by $+P_{BSS}(t)$ and expressed as:

$$+P_{BSS}(t) = \frac{\left(SOCU - SOC(t)\right) \times C_{bat} \times N_{bat}}{\Delta t} \tag{4}$$

consequently, $-P_{BSS}(t)$ shows the amount of power that BSS can supply continuously before reaching its minimum limit (SOCL) during one time-step (hour):

$$-P_{BSS}(t) = \frac{(SOC(t) - SOCL) \times C_{bat} \times N_{bat}}{\Delta t} \tag{5}$$

for longevity of battery system, the SOC of BSS should remain between SOCU and SOCL limit. The SOCU and the SOCL are set as 90% and 10%, respectively.

3.1.3. Inverter model

In HES, the inverter is used to convert DC power generated by the PV system or stored in the batteries that can be supplied to load. During the conversion process, some power is lost due to the inefficiency of the inverter. To model the inverter, the losses that occur during the conversion process must be taken into account [24]. This can be done using the inverter efficiency (η_{inv}), which represents the percentage of the input power that is converted into output power. The output power (in kW) of the inverter after taking into account the peak load demand (P_{Load_Peak}) of the system and the inverter efficiency (η_{inv}) can be calculated using the following (6):

$$P_{Inv} = \frac{P_{Load\_Peak}}{\eta_{inv}} \tag{6}$$

3.1.4. Diesel generator model

Diesel generator serves as backup energy source. The generator starts when no other sources (PV and BSS) can satisfy load during load shedding. The power output of a diesel generator is given in (7).

$$P_{DG}(t) = P_n * \eta_{DG} \tag{7}$$

Where P_n represents the nominal power (in kW) provided by the manufacturer while P_{DG} is the power generated (also in kW). Accordingly, η_{DG} reflects generator efficiency. For the considered community load, Perkins diesel generator of MP-33P/50Hz specification is selected as it can sustain peak load demand [25].

3.1.5. Intermittent grid model

The grid is commonly perceived as an inexhaustible power source that can readily meet the demanded load at any given time. The power output from the grid can be represented mathematically by considering load demand and the availability of power from the grid:

$$P_{Grid}(t) = R_{Grid}(t) \times P\_Load(t) \tag{8}$$

here R_{Grid} indicates the reserve capacity margin needed to ensure secure system operation during unexpected high demand. In this study, R_{Grid} is considered 1.2 for the intermittent grid. Due to load shedding, the grid's supply is not continuous, and therefore the electricity available to consumers is dependent on the schedule of load shedding. The grid's behavior is modeled as a binary variable (B_{Grid}), indicating power supply availability

(B_{Grid}=1) or unavailability (B_{Grid}=0) at a specific hour. It is emphasized that the grid can satisfy the load only when B_{Grid} is equal to 1. The schedule of grid power outage and its availability is governed by load shedding practices. This concept of binary state power supply is also followed by relevant studies in [4], [26].

$$P_{Grid}(t) = \begin{cases} B_{Grid}(t) \times P\_Load(t), B_{Grid}(t) > 0 \\ 0, B_{Grid}(t) = 0 \end{cases} \tag{9}$$

3.1.6. Communication system

A robust communication system between different components of HES is vital to ensure uninterrupted power supply operation. This system must transfer continuous and accurate power information to EMS from PV, BSS, diesel generator, grid, and the load demand. Communication is crucial for the successful operation of HES to overcome various uncertainties in the system such as load demand fluctuations, PV intermittency and grid vulnerabilities. Based on the information and timely communication, the EMS controller performs the real time execution without the presence of any human operator. Depending upon the speed and the area requirement, different communication technologies used in the HES in literature are presented in Figure 4. Some commonly used technologies are Narrow band power line communication (NB-PLC), digital subscriber line (DSL), passive optical network (PON), bluetooth, wireless fidelity (Wi-Fi) and Worldwide interoperability for microwave access (Wi-MAX) [27].

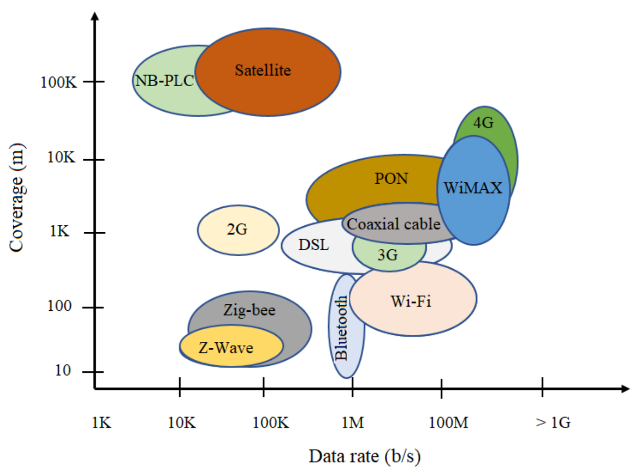

Figure 4. Different communication technologies used in HES

4. THE RULE-BASED ENERGY MANAGEMENT SCHEME

In systems like HES that utilize multiple energy sources, the role of EMS is crucial [28], [29]. The proposed EMS has three main objectives: i) to make sure power supply availability during intervals of load shedding, ii) to maximize the utilization of PV by charging battery system and supplying power to the grid, and iii) to minimize diesel generator operation. To achieve these objectives, the EMS employs one of three distinct modes, based on the availability of power from various sources of HES.

4.1. Grid mode

In this mode, the power is supplied by the grid, if it has enough power to meet the load. If surplus power is available from the grid, the BSS will be charged. This research considers TOU tariff policy, which means that the BSS will be charged from grid only during off-peak hours. During this mode, if the PV system starts generating power, it will also charge the BSS. Charging the BSS from PV while the grid power is available can lead to maximum economic benefits.

4.2. RES mode

This mode is activated when there is no power available from the utility grid (during load-shedding), and power is being supplied by PV and BSS to fulfill the load demand. Nevertheless, due to the variability of PV power and fluctuations in load demand, two situations are possible:

– Situation 1: $P_{PV}(t) > P_{Load}(t)$; the surplus power from PV will charge BSS in case the SOC (current) is lower than SOCU.
– Situation 2: $P_{PV}(t) < P_{Load}(t)$; the BSS power will be used to meet the power deficit If the current state of charge (SOC) is greater than the state of charge lower limit (SOCL).

4.3. DG mode

This emergency mode is not activated during normal HES operation and is only utilized during critical situations. In the event when power from PV and BSS is insufficient to meet the load demand during load-shedding intervals, the DG will be used to cover the energy deficit. The operation of the HES under the proposed EMS control is illustrated in Figure 5.

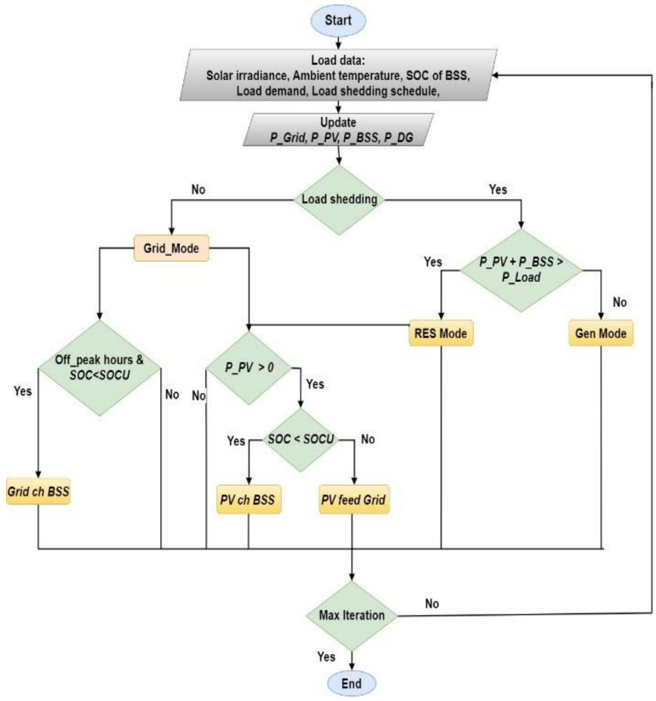

Figure 5. The EMS flowchart for HES

5. RESULTS AND DISCUSSION

The developed methodology is implemented in the MATLAB environment, where EMS determines the suitable HES modes required to fulfill the load demand. Real data sets of weather (for PV) and the load shedding profiles for the location in question are used for simulations. The former is sourced from [20] and the latter from [17]. Simulations are performed using a local load profile with TOU tariff policy divided into peak (18-22 hour) and off peak (remaining 20 hours) periods, as stated in [23]. The optimal sizes of HES components are selected as PV=67.7 kW, BSS=28.8 kWh, and DG=30 kW from [19]. The HES has been tested for a sunny and a cloudy day. The results are presented in Figure 6 and 7, the first plot displays the power supplying modes, such as grid mode, RES mode, and DG mode, in relation to considered load demand. The second plot illustrates the BSS operation and the SOC during charging/discharging processes. Accordingly, the last plot depicts the various PV system modes.

5.1. Sunny day scenario

Figure 6 shows HES operation for a normal sunny day (12 June 2019). Load shedding occurs for a total of 7 hours. These intervals are from hour 3-4, 6-7, 10-12, 14-16, and 18-19 (as given in the first plot). During the load shedding intervals, grid supply is not available and thus alternate sources of power are required. Depending on proposed EMS, PV power is prioritized based on its availability. If PV power is not available (during night or due to clouds), BSS supplies the load. The HES operation utilizing BSS power can be noted in the load shedding intervals at hours 3-4 and 6-7. Conversely, during hours 10-12 and 14-16 at daytime, entire load demand is solely satisfied by PV. During the evening hours of 18-19, the demand is sustained by combining PV and BSS power. Figure 6 shows the coordinated operation of multiple energy sources to ensure uninterrupted power supply in the first plot. Notably, the generator was not needed on a sunny day since there was enough energy from PV and BSS to meet the load demand. The second plot illustrates the BSS's operation, where the negative curve represents the battery discharge during grid outage intervals. The SOC curve also displays variations resulting from the BSS charging and discharging. The power output from BSS is determined by (10).

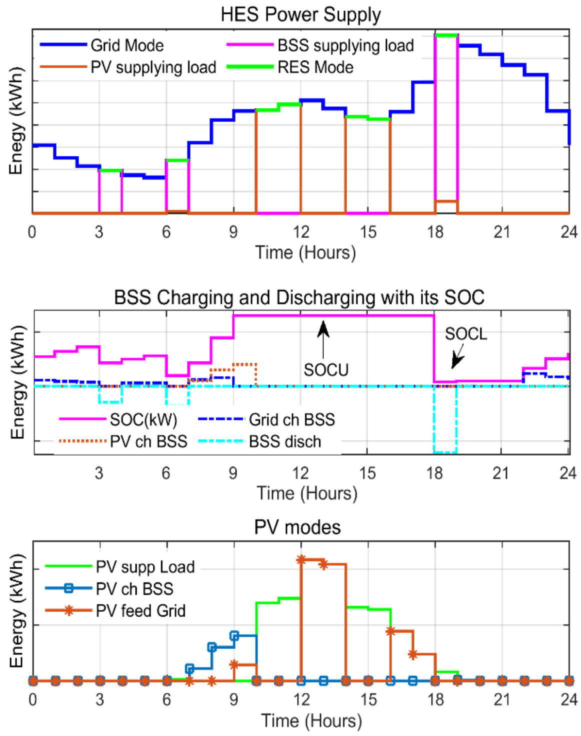

Figure 6. Performance of HES under the control of EMS during a typical sunny day

$$P_{BSS}(t) = \frac{P_{Load}(t)}{\eta_{inv}} - P_{PV}(t) \quad (10)$$

The (10) may yield $P_{BSS}(t) < 0$ due to the intermittent behavior of PV, indicating that surplus PV energy being absorbed by BSS considering the limits set by (4) and (5). In the third plot, various modes of PV system are illustrated explaining how PV injects surplus power to the grid. It is worth noting that PV power injecting to grid takes place after the load demand is met and BSS is fully charged. PV power feeding the grid operation can be observed during specific hours, such as 12-14 and 16-18. The PV feeding grid approach not only utilizes PV energy efficiently but also reduces PV curtailment, resulting in economic advantages for HES.

5.2. Cloudy day scenario

The cloudy day operation of HES for a specific day on 15th August 2019 indicating lower irradiance levels is illustrated in Figure 7. Besides, the concerned day demand profile and the hourly shedding also differ with grid outage occurring at hours 6-7, 8-10, 16-17, and 18-19. As PV could not generate adequate power due to lower levels of solar irradiance, BSS assisted PV to meet the load requirements during the daytime. The integrated operation of PV and BSS at the time of grid outage at hours 6-7, 9-10, and 16-17 is required while during hours 8-9 and 18-19, DG mode had to be activated as PV and BSS could not sustain the required demand (as shown in the second plot of Figure 7). While the DG is operating, PV power is used to charge the BSS (PV ch BSS operation). The third plot displays the PV modes of operation during the corresponding cloudy day. As expected, HES successfully ensured uninterrupted power supply to demanded load even in cloudy weather conditions through effective integration of its sources (PV, BSS, and DG). The simulation results prove the robustness of HES under normal as well as extreme environments.

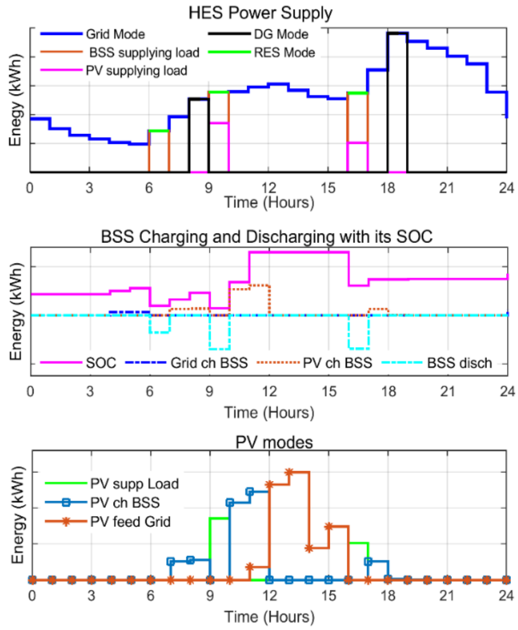

Figure 7. Performance of HES under the control of EMS during a typical cloudy day

6. CONCLUSION

This paper illustrates the application of hybrid energy system (HES) comprising a combination of photovoltaic (PV), battery storage system (BSS), and diesel generator (DG) to overcome the impact of load shedding at distribution feeder level in an electrical grid network. The proposed system operates in three different modes, namely grid mode, RES mode, and DG mode, ensuring continuous power supply regardless of grid outage. The effectiveness of the HES is evaluated under variable load and different weather conditions during sunny and cloudy days. Findings of this study reveal that HES equipped with intelligent energy management scheme can successfully overcome load shedding issues while minimizing diesel generator operation and the cost of electricity. In future research, the implementation of an HES pool, which connects two or more HES to evaluate their efficacy, is recommended. Additionally, other renewable sources such as wind, locally produced biomass, and biogas can be combined into the HES. Furthermore, a life cycle cost assessment of HES should be conducted to evaluate its economic viability in comparison with other alternatives such as diesel generators and UPS system.

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