Energy management and economic analysis of multiple energy storage systems in solar PV/PEMFC hybrid power systems

Vipin Das1 | Asheesh K. Singh1 | PitchaiVijaya Karuppanan1 | Pradeep Kumar2 | Sri Niwas Singh3 | Vassilios Georgios Agelidis4

1 Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India
2 National Institute of Technology Kurukshetra, Kurukshetra, India
3 Indian Institute of Technology Kanpur, Kanpur, India
4 Technical University of Denmark, Lyngby, Denmark

Correspondence
Asheesh K. Singh, Motilal Nehru National Institute of Technology Allahabad, India.
Email: asheesh@mnnit.ac.in

Abstract
This study proposes an energy management system (EMS) to manage a standalone hybrid power system (HPS) comprising solar photovoltaic (PV), proton exchange membrane fuel cell (PEMFC), and a battery energy storage. The battery and a hydrogen storage system in PEMFC provide short- and long-term electricity storage, respectively. The EMS ensures electrical efficiency during normal/abnormal operation of the HPS and related limitations, namely unexpected variations in solar irradiance and loads, PEMFC cold start, and battery charging status. The proposed EMS is evaluated using mathematical modelling, simulation studies, and real-time digital simulation. The results show that the proposed EMS is resilient to complex solar PV/load power changes and keeps the dc-link voltage in place. The viability of the proposed HPS is analysed using daily average solar insolation and load profiles. This analysis is useful to schedule problems of load/generation. The economic analysis of the proposed EMS, done using Homer pro, ensures that the HPS operates cost-effectively.

KEYWORDS
Battery energy storage system, Economic analysis, Energy management system, Hybrid power system (HPS), Hydrogen energy storage, Solar PV/PEMFC

1 INTRODUCTION

Renewable energy sources (RESs) are used in power grids to deliver clean energy to consumers. The RESs are uncontrollable, as they are nature-dependent to generate electricity [1]. Thus, it becomes difficult to plan and use RESs. Energy storage system (ESSs) such as fuel cells and batteries can help solve the aforementioned issues by injecting the required energy into the network grid, thereby making the process controllable. RESs and ESSs are correlated in various ways [2, 3], depending on the availability and cost. An energy management system (EMS) is required to manage energy sources to optimally fulfil the load demand. The objectives of EMSs differ depending on RESs or algorithms [4–6], such as load fulfilment and cost minimization. EMS algorithms such as fuzzy logic control [7], heuristic algorithm [8], and other soft computing techniques [9] have been used. However, these algorithms are complex and computationally intensive. In addition, most combinations of RESs cannot detect the battery state of charge ($\text{SOC}_{\text{bat}}$) and the slow ramp rate of proton exchange membrane fuel cell (PEMFC; in planning).

This study proposes an EMS, applied to a standalone hybrid power system (HPS), that comprises solar photovoltaic (PV), PEMFC, and lead–acid battery. Solar PV is a commercial low-cost matured RES [1]. PEMFC is a clean energy source, allowing bi-directional energy flow and storing and generating electricity. The generation occurs owing to the energy released caused by chemical reactions [10]. Hydrogen, fuel for PEMFC, is stored in the hydrogen storage system (HSS). High-purity hydrogen is an important requirement for energy generation in PEMFC. It is produced by the electrolysis of water, an eco-friendly carbon-neutral method [11]. Electrolyzers require
48–55 kWh of electricity to supply 1 kg of hydrogen at an efficiency of 65–70%, although the overall production of industrial hydrogen using electrolysis is 4% worldwide [12] owing to the economics involved. However, PEMFC cannot feed dynamic loads owing to difficulties in cold, slow ramp rates, and fluctuations in output voltage ($V_{FC}$) [10]. In addition, the current produced by PEMFC ($i_{fc}$) contains high low-frequency ripples, rendering the system unstable, especially in a grid-connected mode [13]. While PEMFC can store energy itself, its integration with ESS can help feed dynamic loads [14]. Moreover, fluctuations in the solar PV output caused by weather can stress or damage the inverter [15]. The ESS helps overcome power fluctuations at the inverter input and release stress, making solar PV a reliable energy source [16]. However, the high price of ESSs increases the overall system cost [17]. In this study, the lead–acid battery acts as an ESS.

As an HSS in a PEMFC serves as energy storage, in this study, the combination of lead–acid battery and HSS is called multiESS (MESS). The proposed EMS uses the voltage and current parameters of the solar PV, ESS, and DC and AC buses to share power among energy sources, MESS, and loads. The EMS controls the power flow to qualitatively and quantitatively maintain equilibrium between generation and consumption. Many studies mention several control strategies for the charging and discharging of batteries [18]. In this study, the maximum self-consumption of the power generated from solar PV [19] can charge the battery. Previously, the excess $P_{pv}$ was used to diminish in dump loads [20]. This study proposes to store the excess $P_{pv}$ in HSS as hydrogen. Moreover, the PEMFC and battery operation can help overcome load fluctuations. The proposed EMS algorithm, considering standalone HPS, is evaluated in the following scenarios:

i. Scenario 1: Variable $P_{pv}$ and constant $P_{Load}$
ii. Scenario 2: Variable $P_{pv}$ and variable $P_{Load}$
iii. Scenario 3: Effect of fault on the EMS
iv. Scenario 4: HPS analysis using daily average solar insolation profiles

The proposed EMS is evaluated in Scenarios 1 and 2 under normal conditions and in Scenario 3 under dynamic operating conditions, whereas the long-term system operation is observed in Scenario 4.

The EMS estimates the availability of the communication system to transmit and collect data from each source and method. The proposed research states the following findings:

i. The proposed design removes energy wastage in dump loads and allows adequate energy storage in HSS.
ii. The ESS integration helps overcome variations at the input terminal of the inverter.
iii. The proposed EMS is simple, fast, and efficient in computation.
iv. The EMS stabilizes $V_{dc,act}$ regardless of source power variations.
v. According to SOC$_{bat}$ and $P_{pv}$, the EMS switches among the battery, PEMFC, and electrolyzer.

The rest of the paper is structured as follows: Section 2 details various components of the proposed system. Section 3 analyses the economic feasibility of the system using Homer Pro and compares it with the existing literature. Section 4 discusses the specifications and control methods for the power device. Section 5 deals with the planned EMS. Section 6 analyses the results, and Section 7 concludes the paper.

2 | SYSTEM MODELLING

Figure 1 shows the considered off-grid HPS. The solar PV array and PEMFC are connected to a common DC-link using a boost converter and a bi-directional DC–DC converter, respectively. Moreover, the bi-directional DC–DC converter (BDCC) connects the battery to the DC-link, whereas HSS is a part of PEMFC. The DC-link is a 5000-µF capacitor with $V_{dc,ref}$ of 700 V. The mathematical models of the solar PV and the MESS...
components used in the HPS are discussed. The values of different parameters considered are mentioned in Section 6.

2.1 Solar PV array model

The solar PV array is a combination of series ($N_S$) and parallel ($N_P$) connected PV modules [21]. According to semiconductor technology, a solar cell generates 0.7–1.2 V [2]. Here, each solar PV cell is modelled as a single diode circuit equivalent with a parallel current source (Figure 2(a)). The relationship between $V_{pV}$ and $I_{pv}$ is provided in (1).

$$I_{pv} = N_P I_{ph} - N_P I_0 [K] - N_P/N_S V_{pV} + IR_s/R_{sh},$$

(1)

where

$$K = \exp \left( \left( \frac{V_{pV}}{N_S} + \frac{IR_s}{N_P} \right) / \left( nkT/q \right) \right) - 1.$$

2.2 Battery model

The equivalent circuit of the battery is shown in Figure 2(b) [22]. $v_{bat}$ and $SOC_{bat}$ are calculated in (2) and (3), respectively.

$$v_{bat} = n_b E_b \pm n_b R_{bat} \times i_{bat},$$

(2)

($i_{bat} > 0$, charging; $i_{bat} < 0$, discharging)

$$SOC_{bat} = 1 - Q/C_{bat},$$

(3)

The SOC_{bat} limits are set in the range of 20–80% [23].

2.3 PEMFC model

PEMFC is an electrochemical component that generates electricity using chemical reactions [24]. $V_{FC}$ is calculated as shown below:

$$V_{FC} = E_{Nernst} - (V_{act} + V_{ohm} + V_{con}).$$

(4)

The equivalent PEMFC circuit is shown in Figure 3(a), where different losses are described as resistance equivalent, $R_{act}$, $R_{con}$, and $R_{ohm}$. The boost mode of BDCC increases $V_{FC}$ to a $V_{dc,ref}$ level. The PEMFC is presumed to be in “on” condition in the present function to avoid cold start.

2.4 Electrolyzer and HSS

The electrolyzer electrolyses the water to generate hydrogen at a rate defined in (5) [25, 26]. The hydrogen is stored in HSS at a pressure defined by (6) to be utilized by PEMFC as per the load requirement. The equivalent circuit of the electrolyzer is shown in Figure 3(b). The source represents the reversible voltage obtained from Gibbs free energy caused by chemical reactions. Figure 3(b) shows the ESR of the electrolyzer cell [25].

$$\mu_{H_2} = \eta_F n_C i_e / F$$

(5)

$$P_b - P_{bi} = Z (RT_b / V_b)$$

(6)

The capacity of HSS is based on the maximum amount of hydrogen produced during electrolysis.

3 ECONOMIC ANALYSIS

The economic analysis of the standalone HPS is performed using Homer pro [27]. The following two parameters have been considered: net present cost (NPC) and cost of energy (COE). NPC is the present installation value and lifetime operation cost of the system. It is calculated based on the total annualized cost.
TABLE 1  Cost of main components of HPS

| Equipment      | Cost  |
|----------------|-------|
| Converter      | 950 $/kW |
| PEMFC          | 1840 $/kW |
| Electrolyzer   | 1500 $/kW |
| Hydrogen tank  | 230 $/kg |
| Solar-PV       | 1000 $/kW |

FIGURE 4  Cash flow diagram of the standalone HPS

($) per kWh (year) and capital recovery factor. COE is the “average cost per kWh” of usable electricity produced by the system. The COE is expressed as follows:

\[ \text{COE} = \frac{C_{an,n,t}}{E}. \]  

The economic feasibility of the proposed HPS has been evaluated considering two schemes:

i. Scheme 1: Total load supplied by the utility
ii. Scheme 2: Total load supplied by standalone HPS

Each scheme was evaluated to determine the most suitable power delivery scheme. Table 1 lists the cost of the main system components. The performance data of the equipment and the related cost are obtained from [27]. The cash flow diagram obtained during simulation with Homer Pro is shown in Figure 4. It shows the superior performance of the considered HPS, that is, Scheme 2 over Scheme 1. The analysis of NPC and COE is listed in Table 2.

4 | CONTROL STRATEGIES

Different control strategies to control the system components described in Section 2 are discussed in this section. These strategies are vital for operation and control.

4.1 | Solar PV control

The solar PV controller includes the maximum power point tracking (MPPT) controller to extract maximum power from the solar photovoltaic [28–31] and another control method to maintain constant DC-link voltage (700 V). The error signal of the MPPT controller is passed through the proportional integral (PI)-1 controller to reduce the steady-state error, providing D1 (the MPPT control duties ratio). The second control loop comprises a DC-link voltage regulator, in which the DC-link voltage is compared with the reference value (700 V), and the error signal is transmitted using the PI-2 controller for a steady-state error reduction. The PI-2 output supplies the duty ratio D2 for DC-link voltage variations. Comparing the aforementioned duty ratios, the duty ratio or duty cycle for the DC–DC boost converter is produced (Figure 5(a)).

4.2 | VSI control

A voltage source inverter (VSI) converts \[ V_{dc\text{-act}} \] to 3-ϕ AC voltage, using a dual-loop control strategy (Figure 5(b)). In a dual-loop control method, the first loop maintains \[ V_{dc\text{-act}} \], and the second loop regulates \[ I_d \] and \[ I_q \]. Inputs of the controller include load voltage \( V_{abc} \), load current \( I_{abc} \), and regulated \( V_{dc\text{-act}} \). To produce reference voltages \( U_{abc\text{,ref}} \), the current regulator transforms \( V_{abc} \) into \( V_d \) and \( V_q \). The \( d \) and \( q \) components enable independent control of real and reactive power. The reference for \( I_q \) is considered as zero to ignore the reactive power generated by the VSI. The reference generator uses \( V_{dc\text{-act}} \) and phase-locked loop (PLL) to provide \( U_{abc\text{,ref}} \). To produce VSIPWM signals, \( U_{abc\text{,ref}} \) is compared with \( V_d \) and \( V_q \).

4.3 | PEMFC and battery control

The PEMFC and battery operate as the two-part control strategy shown in Figure 5(c), that is, battery management system (BMS) and PEMFC management system (PEMFCMS). During BMS, the BDCC operates in the buck and boost modes to charge and discharge the battery, respectively. Moreover, PEMFCMS performs two operations: electrolyzer control, that is, the controller activates hydrogen production; and hydrogen discharge, that is, the controller enables the hydrogen discharge by activating the PEMFC.

The occurrences of circulating currents, caused by the parallel operation of power converters, are avoided by the EMS, and the sources are isolated using a relay.
FIGURE 5  Control strategy and EMS modes for a) DC–DC boost converter, b) voltage source inverter, and c) battery and fuel cell stack
5 | EMS ALGORITHM

The proposed EMS shares power among loads, generation, and MESS using the following system parameters: $V_{pv}$, $I_{pv}$, $V_{dc-ref}$, $V_{dc-ref}$, $I_{dc-ref}$, $V_{bat}$, and SOC$_{bat}$. Modes are decided based on the availability of $P_{pv}$. Each mode may have sub-modes depending on the availability of ESS. The sub-modes or selection of ESS depends on SOC$_{bat}$ limits, as discussed in Section 2. The flowchart is shown in Figure 6(a).

5.1 | Mode 1: Power surplus mode ($P_{pv} > P_{Load}$)

In Mode 1, surplus $P_{pv}$ is available. A part of $P_{pv}$ feeds the load, and the remaining part is stored in the ESS. The ESS is selected based on SOC$_{bat}$, which is provided as two sub-modes:

i. Battery charging sub-mode (BCSM)

ii. Hydrogen storage sub-mode (HSSM)

The algorithm helps select battery as energy storage if SOC$_{bat}$ ≤ 80% and enter into the BCSM. If SOC$_{bat}$ ≥ 80%, the algorithm selects HSS for energy storage, which is termed as HSSM. In the BCSM, BDCC operates as a buck converter to charge the battery with $i_{bat-ref}$ given in (9), up to SOC$_{bat} = 80\%$. The difference between $i_{bat-ref}$ and $i_{bat}$ is fed to the PI controller (PI-3) (Figure 5(c)). The PI controller output is compared with a 15-kHz triangular carrier wave to generate the BDCC switching signal. $P_{Load}$ in BCSM is provided in (8). In HSSM, the electrolyzer generates hydrogen using the excess $P_{PV}$ and stores it in HSS. Here, the electrolyzer control (Figure 5(c)) becomes active. The equation of $P_{Load}$ is given in (10).

$$P_{Load} = P_{pv} - P_{bat}.$$  \hspace{1cm} (8)

$$i_{bat-ref} = \left( P_{pv} - P_{Load} \right) / v_{bat}.$$ \hspace{1cm} (9)

$$P_{Load} = P_{pv} - P_{el}.$$ \hspace{1cm} (10)

5.2 | Mode 2: Power deficiency mode ($P_{pv} < P_{Load}$)

In Mode 2, $P_{pv}$ is less than the load demand. Therefore, the MESS provides deficit power. The BDCC operates in the boost mode to discharge the battery until SOC$_{bat}$ is 20%. Depending on SOC$_{bat}$, this mode can be further divided into

(i) Battery discharge sub-mode (BDSM)

(ii) Hydrogen discharge sub-mode (HDSM)

In BDSM, the battery discharges to supply the deficit power, as defined in (11); yet, the control in BDSM is similar to that in BCSM.

$$P_{Load} = P_{pv} + P_{bat}.$$ \hspace{1cm} (11)

The PEMFC uses the hydrogen from the HSS to generate power, $P_{f}$, given as

$$P_{Load} = P_{pv} + P_{f}.$$ \hspace{1cm} (12)
If both the battery and hydrogen storage have sufficient capacity, the battery will be given priority owing to the high ramping rate of the battery.

5.3 Mode 3: Power balanced mode ($P_{pv} = P_{load}$)

In Mode 3, $P_{pv}$ can feed $P_{load}$, as given in (13).

$$P_{pv} = P_{load}. \quad (13)$$

The flow chart of the EMS algorithm and the flow diagram indicating power flow in the aforementioned modes are shown in Figure 6(a) and Figure 6(b)–(d), respectively.

6 RESULTS AND DISCUSSION

A robust EMS should meet the load demand, under all circumstances, while managing energy sources and energy storage. The performance of the proposed EMS is analysed considering the following four scenarios in real-time using OPAL-RT OP5700® with RT-LAB® [32] and Simulink® interface:

(i) Scenario 1: Variable $P_{pv}$ and constant $P_{load}$

(ii) Scenario 2: Variable $P_{pv}$ and variable $P_{load}$

(iii) Scenario 3: Effect of fault on the EMS

(iv) Scenario 4: HPS analysis using daily average solar insolation profiles.

For each scenario, the values of different parameters of each component discussed in Section 2 are listed in Table 3. During the study, the parameters monitored are MESS response; MESS voltage and current response; load voltage and current; and VSI output. In each scenario, three different cases, namely, Case-1: $SOC_{bat} < 20\%$, Case-2: $SOC_{bat} = 50\%$, and Case-3: $SOC_{bat} \geq 80\%$, are considered. The $SOC_{bat}$ is selected based on the upper and lower limits of the battery SOC, as discussed in Section 2. In the first three scenarios, the same changed pattern of irradiance is used, whereas in Scenario 4, simulations are performed for a whole day with varying irradiance. The study is evaluated based on the tracking of the load profile using the HPS.

6.1 Scenario 1

In Scenario 1, $P_{load}$ is constant, and $P_{pe}$ varies (Table 4) owing to a change in solar irradiance.

6.1.1 Case 1 ($SOC_{bat} < 20\%$)

In this case, $SOC_{bat} = 10\%$, and the solar irradiance varies, as listed in Table 4. The system response, as shown in Figure 7(a), depicts that from 0 to 0.1 s, $P_{pe} = 59$ kW. As $P_{pe} < P_{load}$ and $SOC_{bat} < 20\%$ (minimum $SOC_{bat}$), the EMS activates Mode-2 and the sub-mode—HDSM. Therefore, the HSS provides hydrogen to the PEMFC to generate the remaining power, that is, 16 kW. At 0.1 s, an increase in irradiance results in $P_{pe} = 79$ kW, which is more than $P_{load}$. As $SOC_{bat} < 20\%$, the EMS activates Mode 1 and sub-mode, BCSM. Thus, solar PV feeds the load (75 kW), and the excess power (4 kW) charges the battery. From 0.2 to 0.3 s, $P_{pe} = 100$ kW. As $P_{pe} > P_{load}$ and $SOC_{bat} < 20\%$, the EMS continues to operate in Mode 1 and BCSM. From 0.3 to 0.4 s, despite reduction in irradiance,
The voltage and current waveforms of the system (Figure 7(b)) shows that irrespective of the operating condition, $V_{\text{dc,act}} = 700 \text{ V}$. Under varying $P_{\text{pv}}$, $V_{\text{pv}}$ is maintained. However, $I_{\text{pv}}$ changes with $P_{\text{pv}}$, which reflects the resilient nature of the EMS. Figure 7(c) shows the response of PEMFC up to 0.1 s, during which $P_{\text{pv}}$ and SOC of the battery have been low. The PEMFC provides 31 A at 515 V to the load. Three-phase VSI output and DC-link voltage are shown in Figure 7(d). Figure 7(e) shows the in-phase operation of phases A and B.

### 6.1.2 Case 2 (SOC$_{\text{bat}} = 50\%$)

The response of Case 2 is similar to Case 1 but with battery only. Using the irradiance levels listed in Table 6, the response is plotted (Figure 8(a)) at 0–0.1 s and $P_{\text{pv}} = 59 \text{ kW} (<P_{\text{Load}})$, at which

$$P_{\text{pv}} > P_{\text{Load}} \text{ and SOC}_\text{bat} < 20\%.$$ Therefore, the previous mode and sub-modes remain active.

The voltage and current waveforms of the system (Figure 8(b)) shows that irrespective of the operating condition, $V_{\text{dc,act}} = 700 \text{ V}$. Under varying $P_{\text{pv}}$, $V_{\text{pv}}$ is maintained. However, $I_{\text{pv}}$ changes with $P_{\text{pv}}$, which reflects the resilient nature of the EMS. Figure 8(c) shows the response of PEMFC up to 0.1 s, during which $P_{\text{pv}}$ and SOC of the battery have been low. The PEMFC provides 31 A at 515 V to the load. Three-phase VSI output and DC-link voltage are shown in Figure 8(d). Figure 8(e) shows the in-phase operation of phases A and B.
6.1.3 | Case 3 \( (\text{SOC}_{\text{bat}} > 80\%) \)

In Case 3, the battery is charged fully. Therefore, the electrolyzer uses excess \( P_{pe} \). Figure 9(a) shows the system response with the same irradiance levels and \( P_{pe} \) as in Case 1. At 0–0.1 s, \( P_{pe} < P_{L,load} \) therefore, BDSM (in Mode 2) gets activated. The battery complements the solar PV to furnish the remaining power of 16 kW. At 0.1–0.2 s, \( P_{pe} > P_{L,load} \). During this period, the HSSM (in Mode 1) gets activated to feed the extra power to the electrolyzer. A similar operation has been observed at 0.2–0.3 s. The voltage and current of various sources are shown in Figure 9(b). \( n_e \) and \( i_e \) are shown in Figure 9(c). At 0.1–0.2 s, \( i_e \) is 8 A, which increases to 50 A at 0.2–0.3 s. At 0.3 s, \( P_{pe} \) becomes low. Thus, \( i_e \) becomes zero, and the battery provides 32.6 A of current. The VSI outputs, \( V_{abc} \) and \( V_{dc-act} \) are maintained irrespective of the varying irradiance. The in-phase operation of the system is shown in Figure 9(e).

The lifetime of VSI depends on the operating environment and load. \( P_{pe} \) at input terminals reduces the life of VSI; however, the ESS, acting as a buffer, absorbs sudden changes in the power to increase the life of VSI [15,16]. Figure 10 shows the VSI loading with and without MESS.

6.2 | Scenario 2

In Scenario 2, a random load variation marked as \( P_{L,load,ref} \) in Figure 11(a), is used for analysis. The change in load at each time interval is listed in Table 5. Based on \( \text{SOC}_{\text{bat}} \), the following cases have been considered:
6.2.1 | Case 1 (SOC\textsubscript{bat} < 20\%)

For SOC\textsubscript{bat} = 10\%, the system operates the BCSM in Mode 1 and the HDSM in Mode 2. The power flow among the components is shown in Figure 11(a). At 0–0.1 s, \( P_{pv} \) (59 kW) < \( P_{load} \) (75 kW); therefore, the remaining power demand (16 kW) is fed by PEMFC, as the HDSM is active. At 0.1–0.12 s, \( P_{pv} \) (79 kW) > \( P_{load} \) (75 kW). The excess power is used to charge the battery. At 0.12–0.18 s, \( P_{load} \) (100 kW) > \( P_{pv} \) (79 kW). Thus, the HDSM gets activated, and the PEMFC provides 21 kW. At 0.18 s, \( P_{load} \) (50 kW) < \( P_{pv} \) (79 kW). The battery stores the excess power of 46 kW. At 0.2 s, \( P_{pv} \) = 100 kW and \( P_{load} \) = 75 kW; the remaining power demand of 25 kW is supplied by the battery. At 0.34 s, \( P_{pv} \) is 79 kW and \( P_{load} \) is 125 kW; the power requirement of 46 kW is delivered by the battery. At 0.34–0.4 s, \( P_{load} \) is reduced to 60 kW and \( P_{pv} \) is 79 kW. The battery accepts the extra power. The current and voltage of each source, in this case, are shown in Figure 11(b) and Figure 11(c), respectively. \( P_{pv} \) and \( P_{load} \) track the changes in the current source. The voltage and current at VSI terminals are shown in Figure 11(d), in which the variations in \( P_{load} \) are reflected in the load current. Moreover, the load current follows the load changes instantaneously.

6.2.2 | Case 2 (SOC\textsubscript{bat} = 50\%)

Figure 12(a) with \( P_{pv} \), \( P_{pe} \), \( P_{elect} \), and \( P_{bat} \) shows that at 0–0.1 s, \( P_{pv} \) = 59 kW and \( P_{load} \) = 75 kW. The battery supplies the excess \( P_{load} \) of 16 kW. At 0.1–0.12 s, \( P_{pv} \) = 79 kW and \( P_{load} \) = 75 kW. The battery uses the excess power of 4 kW. At 0.12–0.18 s, \( P_{load} \) increases to 100 kW, and \( P_{pe} \) remains at 79 kW. The battery delivers excess power of 21 kW. At 0.18 s, \( P_{load} \) instantly reduces to 50 kW, and \( P_{pe} \) remains at 79 kW. The remaining power is stored in the battery. At 0.2 s, \( P_{pe} \) increases to 100 kW, and \( P_{load} \) remains at 50 kW. The excess power is stored in the battery. At 0.25 s, \( P_{load} \) is 125 kW and \( P_{pe} \) is 100 kW; the power demand of 25 kW is supplied by the battery. At 0.34 s, \( P_{pe} \) is 79 kW and \( P_{load} \) is 125 kW; the power requirement of 46 kW is delivered by the battery. At 0.34–0.4 s, \( P_{load} \) is reduced to 60 kW and \( P_{pe} \) is 79 kW. The battery accepts the extra power. The current and voltage of each source, in this case, are shown in Figure 12(b) and Figure 12(e), respectively. \( P_{pe} \) and \( P_{load} \) track the changes in the current source. The voltage and current at VSI terminals are shown in Figure 12(d), in which the variations in \( P_{load} \) are reflected in the load current. Moreover, the load current follows the load changes instantaneously.

6.2.3 | Case 3 (SOC\textsubscript{bat} > 80\%)

In this case, SOC\textsubscript{bat} = 90\%. The system operates in HSSM (in Mode 1) and BDSM (in Mode 2). \( P_{pv} \), \( P_{pe} \), \( P_{elect} \), and \( P_{bat} \) are shown in Figure 13(a), where at 0–0.1 s, \( P_{pv} \) = 59 kW and \( P_{load} \) = 75 kW. As \( P_{load} \) > \( P_{pv} \), the remaining power of 16 kW is supplied by the battery. At 0.1–0.12 s, \( P_{pv} \) = 79 kW and \( P_{load} \) = 75 kW; the excess power of 4 kW is used by the electrolyzer. At 0.12–0.18 s, \( P_{load} \) = 100 kW and \( P_{pe} \) = 79 kW. The battery supplies the remaining power of 21 kW. At 0.18 s, \( P_{load} \) is reduced to 50 kW and \( P_{pe} \) is 79 kW. As \( P_{pe} \) > \( P_{load} \), the excess power is used by the electrolyzer. At 0.2 s, \( P_{pe} \) = 100 kW and \( P_{load} \) = 50 kW, the excess \( P_{pe} \) is stored in the battery. At 0.25 s, \( P_{load} \) increases to 125 kW and \( P_{pe} \) remains at 100 kW; the battery supplies the remaining power. At 0.34 s, \( P_{pe} \) is 79 kW and \( P_{load} \) is 125 kW. The battery supplies the remaining power of 46 kW. At 0.34–0.4 s, \( P_{load} \) is 60 kW and \( P_{pe} \) is 79 kW. The electrolyzer uses excess power of 19 kW. The current and voltage of each source...
are shown in Figure 13(b) and Figure 13(c). In this case, the load current reflects the variation in $P_{\text{Load}}$ as shown in Figure 13(d).

### 6.3 Scenario 3

In this scenario, a line to ground fault is created at load terminals. Case 1 (SOC$_{\text{bat}} < 20\%$) has been considered for analysis. Similar responses are obtained for Cases 2 and 3; hence, their results have been omitted owing to space constraints. The fault is applied during 0.1–0.15 s. Figure 14(a) shows that during the fault, the phase voltage reduces to zero, and the current increases. The voltage and current regain their previous states immediately after the fault clearance. Figure 14(b) shows that the sources kept generating during the fault. The EMS maintains its performance during the fault conditions, and $P_{\text{Load}}$ tracks $P_{\text{Load,ref}}$. $P_{\text{Load}}$ gets disturbed during the fault, but as soon as the fault is cleared, the EMS starts tracking $P_{\text{Load,ref}}$. The
comparison of the proposed EMS with the existing EMS [33–35] is listed in Table 6. It shows the superior performance of the proposed EMS over other algorithms.

![Figure 14](image_url) Fault analysis on the HPS: (a) Inverter terminal voltage and current; (b) power generated by each source

![Figure 15](image_url) Monthly average solar insolation level [27]

### Table 6

| EMS | Response time (in cycles) | Ref. [33] | Ref. [34] | Ref. [35] | Proposed |
|-----|--------------------------|-----------|-----------|-----------|-----------|
|     | During load change       | 1         | 12        | 0.3       | 0.1       |
|     | During starting          | 2         | 20        | 0.5       | 0.35      |

For long-term performance evaluation, simulations are conducted over 24 h using average solar insolation data [27]. The monthly average data for solar irradiance, with a resolution of 1 min, from 9:00 AM to 5:00 PM is shown in Figure 15. For the remaining period, the MESS should support the load. The average load profile of the day is shown in Figure 16. The load is of an academic building [27], varying from 50 to 125 kW. The load schedule is listed in Table 7. Figure 17(a) shows 24-h energy management for Case 1 (SOC_{bat} < 20%). In this case, the EMS activates Mode 2 (HDSM). As a result, the PEMFC supports the loads whenever \( P_{pv} \) is unavailable. The battery charges itself, using the excess \( P_{pv} \) whenever available. Figure 17(b) shows energy management for Case 2 (SOC_{bat} = 50%). In this case, the battery supports the loads in the absence of \( P_{pv} \). The excess \( P_{pv} \) is diverted to charge the battery. The energy management for Case 3 (SOC_{bat} > 80%) is shown in Figure 17(c). As shown in Figure 17(c), in this case, the battery would support loads whenever \( P_{pv} \) is not available. The excess \( P_{pv} \) is diverted to HSS. In Figure 18, the voltage and current of each source are shown. The three-phase current, voltage, and DC voltage are shown in Figures 19 and 20 for all cases. The load change does not affect the voltage and current of the VSI or the DC-link voltage. The variation of current and the tracking performance of the power are shown in Figure 19(b) and Figure 20(c), respectively. The response times are tabulated in Tables 8 and 9. As the response time is similar in all cases, the results are shown

![Figure 16](image_url) Typical load profile

### 6.4 Scenario 4

For long-term performance evaluation, simulations are conducted over 24 h using average solar insolation data [27]. The monthly average data for solar irradiance, with a resolution of 1 min, from 9:00 AM to 5:00 PM is shown in Figure 15. For the remaining period, the MESS should support the load. The average load profile of the day is shown in Figure 16. The load is of an academic building [27], varying from 50 to 125 kW. The load schedule is listed in Table 7. Figure 17(a) shows 24-h energy management for Case 1 (SOC_{bat} < 20%). In this case, the EMS activates Mode 2 (HDSM). As a result, the PEMFC supports the loads whenever \( P_{pv} \) is unavailable. The battery charges itself, using the excess \( P_{pv} \) whenever available. Figure 17(b) shows energy management for Case 2 (SOC_{bat} = 50%). In this case, the battery supports the loads in the absence of \( P_{pv} \). The excess \( P_{pv} \) is diverted to charge the battery. The energy management for Case 3 (SOC_{bat} > 80%) is shown in Figure 17(c). As shown in Figure 17(c), in this case, the battery would support loads whenever \( P_{pv} \) is not available. The excess \( P_{pv} \) is diverted to HSS. In Figure 18, the voltage and current of each source are shown. The three-phase current, voltage, and DC voltage are shown in Figures 19 and 20 for all cases. The load change does not affect the voltage and current of the VSI or the DC-link voltage. The variation of current and the tracking performance of the power are shown in Figure 19(b) and Figure 20(c), respectively. The response times are tabulated in Tables 8 and 9. As the response time is similar in all cases, the results are shown

![Figure 17](image_url) Energy management for different cases

![Figure 18](image_url) Voltage and current of each source

![Figure 19](image_url) Three-phase current, voltage, and DC voltage

![Figure 20](image_url) Variation of current and tracking performance of the power
TABLE 7  Load scheduling concerning the time

| Time             | Load (kW) | Type of load                                                        |
|------------------|-----------|-------------------------------------------------------------------|
| 12 AM to 10 AM   | 50        | Lighting + fan + air conditioner/room heater                      |
| 10 AM to 12 PM   | 100       | Lab machineries + computers + lighting + fan + air conditioner/room heater |
| 12 PM to 1 PM    | 125       | Lab machineries + computers + lighting + fan + air conditioner/room heater |
| 1 PM to 2 PM     | 75        | Computers + lighting + fan + air conditioner/room heater          |
| 2 PM to 3 PM     | 125       | Lab machineries + computers + lighting + fan + air conditioner/room heater |
| 3 PM to 4 PM     | 100       | Lab machineries + computers + lighting + fan + air conditioner/room heater |
| 4 PM to 5 PM     | 125       | Lab machineries + computers + lighting + fan + air conditioner/room heater |
| 5 PM to 6 PM     | 100       | Computers + lighting + fan + air conditioner/room heater          |
| 6 PM to 7 PM     | 80        | Computers + lighting + fan + air conditioner/room heater          |
| 7 PM to 8 PM     | 75        | Computers + lighting + fan + air conditioner/room heater          |
| 8 PM to 12 AM    | 50        | Lighting + fan + air conditioner/room heater                      |

FIGURE 17  24-h energy management of the HPS: (a) Case-1 (SOC$_{bat}$ < 20%), (b) Case-2 (SOC$_{bat}$ = 50%), and (c) Case-3 (SOC$_{bat}$ > 80%)

FIGURE 18  Voltage and current of various sources for cases 1, 2, and 3 (24-h simulation)
FIGURE 19  Waveforms for the three-phase inverter: (a) current and (b) inverter current waveforms at instant changes in load

FIGURE 20  Waveforms for the three-phase inverter: (a) voltage, (b) DC-link voltage (24 h), and (c) zoomed view of the power output of various sources and storage with respect to load change (24 h)
TABLE 8  Quantitative analysis of results at the starting of the simulation at SOC = 20%

| Quantity                  | $V_{abc}$ | $I_{abc}$ | $P_{pv}$ | $P_{f_i}$ | $P_{elec}$ | $P_{bat}$ | $P_{Load}$ |
|---------------------------|-----------|-----------|---------|----------|-----------|----------|-----------|
| Convergence time (in cycles) | 0.8       | 1.5       | No delay | 0.25     | No delay   | No delay | 1.4       |

TABLE 9  Quantitative analysis of the result during sudden load changes

| Load variation (kW) | Time (in cycles) | $I_{abc}$ (A) | $V_{abc}$ (V) | $P_{pv}$ (kW) | $P_{f_i}$ (kW) | $P_{elec}$ (kW) | $P_{bat}$ (kW) | $P_{Load}$ (kW) |
|---------------------|------------------|---------------|--------------|-------------|-------------|--------------|--------------|---------------|
| 50–100              | 0.125            | No delay      | 0.1          | 0.1         | Battery not involved | 0.5 |
| 100–125             | 0.5              | 0.1           | 0.1          | 0.5         | Electrolyzer not involved | 0.75 |
| 125–75              | 0.125            | 0.1           | 0.3          | 0.5         | 0.5 |
| 75–125              | 0.5              | 0.1           | 0.3          | 0.5         | 0.5 |
| 125–100             | 0.125            | 0.1           | 0.1          | 0.5         | 0.5 |
| 100–100             | 0.125            | 0.1           | 0.1          | 0.5         | 0.5 |
| 125–80              | 0.125            | 0.1           | 0.4          | 0.25        | 0.25 |
| 80–75               | 0.125            | 0.1           | 0.4          | 0.25        | 0.25 |
| 75–50               | 0.125            | No delay      | No delay     | No delay    | No delay |

for Case 1 of Scenario 4 only. In all the load variations, the maximum response time is within the half cycle. This reflects the robustness and computational efficiency of the proposed EMS.

After each set of simulations, that is, of all the three cases for each scenario, $P_{bat}$ equal to 0.3–0.5% of the total capacity (100 kW) has been obtained. Considering the aforementioned value, along with converter and FC heat losses, efficiency of $\approx 93.5\%$ is achieved. In all the cases, the efficiency of the system is higher compared with that of [11] because the system uses an electrolyzer instead of dump loads.

7  | CONCLUSION

This study proposes a dynamic robust EMS for solar PV/PEMFC/BATTERY/HSS. The proposed design helps replace dump loads with adequate storage to improve system performance and reliability. Solar PV and PEMFC are the primary sources of energy, while the battery and HSS form the MESS. The proposed EMS is tested under different operating conditions: (i) variation in loads, (ii) variation in sources, (iii) fault at load terminals, and (iii) 24-h operations. Based on the SOC of the battery and the Solar PV output, the EMS switches between the MESS and Solar PV. Under all circumstances, the EMS is found to do the following functions:

(i) Respond faster to the dynamic changes in solar PV/load power
(ii) Maintain DC-link voltages

The system reliability improves with the simultaneous operation of the battery and electrolyzer, which maintains the power flow. The reliability and longevity of the inverter increase by supplying constant voltage to its input terminals. The proposed EMS monitors and allocates power sources as soon as the load or power supply variation occurs. The results show the superior performance of the proposed EMS.

To prove the practicality of the proposed standalone HPS, the system has been tested for 24 h, and the responses are found to be satisfactory. Finally, the economic analysis of the system has been performed using Homer pro. HPS is an economical alternative for the existing power system. The COE of the proposed HPS is 0.270 $/kWh, which is much lower compared with the grid-connected operation owing to the inclusion of MESS.

NOMENCLATURE

| Symbol | Description | Unit |
|--------|-------------|------|
| $C_1$, $C_2$, $C_3$ | Capacitance values |
| $C_{att}$ | Battery capacity |
| $C_{ann,tot}$ | Total cost of energy/year |
| $E_{Nernst}$ | Nernst reversible voltage |
| $E$ | Total electricity consumption in kWh/year |
| $E_{b}$ | Battery E.M.F. |
| $I_0$ | Saturation current of single solar PV cell |
| $I_{bat-ref}$ | Battery current reference |
| $I_d$ & $I_q$ | Direct and quadrature axis current component |

Faraday’s constant (96485 C/mol)
\[ i_{\text{ph}, \text{ref}} \] Reference PEMFC current
\[ I_{p_h} \] Photocurrent of single solar PV cell
\[ k \] Boltzmann's constant
\[ n \] No. of electrons participated in solar PV conduction
\[ N \] Number of cells in a PV module
\[ n_b \] Number of cells in the battery
\[ n_C \] No. of series electrolyzer cells
\[ N_S, N_P \] Number of series and parallel PV modules
\[ P_b \] The pressure of Hydrogen storage tank (Pascal)
\[ P_{bat} \] Battery power
\[ P_{hi} \] Initial pressure of Hydrogen storage tank (Pascal)
\[ P_{\text{elect}} \] Electrolyzer power
\[ P_{f_i} \] PEMFC power
\[ P_{f_{it}} \] PEMFC output power
\[ P_{\text{Load}} \] Load power
\[ P_{\text{Load}, \text{ref}} \] Load reference power
\[ P_{\text{m}} \] Power loss in the system
\[ P_{\text{pv}} \] Solar PV power
\[ q \] Electron charge (1.6021765 \times 10^{-19} \text{ C})
\[ Q \] Amount of charge stored in the battery
\[ R \] Universal gas constant (8.314 J/mol. K)
\[ R_{\text{act}}, R_{\text{con}}, R_{\text{ohm}} \] Activation, concentric and ohmic losses of PEMFC
\[ R_{bat} \] Internal resistance of battery
\[ R_S, R_{pb} \] Series and parallel resistance of PV cell
\[ S_{1}-S_{11} \] Switching pulses for power converters
\[ T_{\text{d}} \] Temperature of solar PV
\[ t \] Time of operation
\[ T_b \] Temperature of Hydrogen storage tank
\[ U_{\text{d,c,ref}} \] Reference voltage of three-phase VSI controller
\[ V_{abc, \text{ref}}, V_{dc, \text{ref}} \] Three-phase VSI voltage and current
\[ V_{\text{act}}, V_{\text{con}}, V_{\text{ohm}} \] Activation, concentric and ohmic potential of PEMFC
\[ V_b \] Volume of the Hydrogen storage tank
\[ V_{\text{bat}}, V_{i_{\text{bat}}} \] Battery actual voltage and current
\[ V_{d_c}, V_{q} \] Direct and quadrature axis voltage component
\[ V_{dc, \text{act}}, V_{dc, \text{ref}} \] DC-link actual and reference voltage
\[ V_{i_{\text{act}}, i_{\text{ref}}} \] Direct and quadrature reference voltage
\[ V_{\text{FC}} \] Output voltage of PEMFC
\[ V_{\text{FC}, \text{ref}}, V_{i_{\text{FC}}} \] PEMFC voltage and current
\[ V_{\text{pv}}, I_{\text{pv}} \] Peak output voltage and current of solar PV modules
\[ Z \] Compressibility factor of the Hydrogen storage tank
\[ \eta_F \] Faraday's efficiency of electrolyzer
\[ \mu_{12} \] Hydrogen generation rate

to enhance flexibility in micro-grids management. J. Energy Storage 23(April), 202–219 (2019).
2. Panda, A., Mishra, U., Tseng, M.-L., Ali, M.H.: Hybrid power systems with emission minimization: Multi-objective optimal operation. J. Clean Prod. 268, 121418 (2020).
3. Mishra, S.P., Dhar, S., Dash, P.K.: An effective battery management scheme for wind energy systems using multi Kernel Ridge regression algorithm. J. Energy Storage 21(August 2018), 418–434 (2019).
4. Merabet, A., Tarifique Ahmed, K., Ibrahim, H., Begusenane, R., Ghias Amer, M.Y.M.: Energy management and control system for laboratory scale microgrid based wind-PV-battery. IEEE Trans. Sustain. Energy 8(1), 145–154 (2017).
5. Morstyn, T., Hredzak, B., Ageidis, V.G.: Control strategies for microgrids with distributed energy storage systems: An overview. IEEE Trans. Smart Grid 9(4), 3652–3666 (2018).
6. Zhang, Y., Wei, W.: Model construction and energy management system of the lithium battery, PV generator, hydrogen production unit and fuel cell in islanded AC microgrid. Int. J. Hydrogen Energy 45(33), 16381–16397 (2020).
7. Mansiri, K., Sukchhai, S., Sirisamphanwong, C.: Fuzzy control algorithm for battery storage and demand side power management for economic operation of the smart grid system at Naresh University, Thailand. IEEE Access 6(c), 32440–32449 (2018).
8. Rajasekhar, B., Pindoriya, N.M.: Heuristic approach for transactive energy management in active distribution systems. IET Smart Grid 3(3), 406–418 (2020).
9. Zachar, M., Daoutidis, P.: Energy management and load shaping for commercial microgrids coupled with flexible building environment control. J. Energy Storage 16, 61–75 (2018).
10. Liu, G., Qin, Y., Wang, J., et al: Thermodynamic modeling and analysis of a novel PEMFC-ORC combined power system. Energy Convers. Manag. 217(February), 112998 (2020).
11. Giddsley, S., Badwal, S.P.S., Munnings, C., Dolan, M.: Ammonia as a renewable energy transportation media. ACS Sustain. Chem. Eng. 5(11), 10231–10239 (2017).
12. Shiva Kumar, S., Himabindu, V.: Hydrogen production by PEM water electrolysis – A review. Mater. Sci. Energy Technol. 2(3), 442–454 (2019).
13. Kong, L., Yu, J., Cai, G.: Modeling, control and simulation of a photovoltaic/hydrogen/supercapacitor hybrid power generation system for grid-connected applications. Int. J. Hydrogen Energy 44(46), 25129–25144 (2019).
14. Bizon, N.: Hybrid power sources (HPS) for space applications: Analysis of PEMFC/Battery/SMES HPS under unknown load containing pulses. Renew. Sustain. Energy Rev. 105, 14–37 (2019).
15. Sangwongwanich, A., Yang, Y., Sera, D., Blaabjerg, F., Zhou, D.: The impacts of PV array sizing on the inverter reliability and lifetime. IEEE Trans. Ind. Appl. 54(4), 3656–3667 (2018).
16. Yang, Y., Wang, H., Blaabjerg, F., Kerekes, T.: A hybrid power control concept for PV inverters with reduced thermal loading. IEEE Trans. Power Electron. 29(12), 6271–6275 (2014).
17. Hossain, M.A., Pota, H.R., Squartini, S., Zaman, F., Muttaqi, K.M.: Energy management of community microgrids considering degradation cost of battery. J. Energy Storage 22(February), 257–269 (2019).
18. Ciupageanu, D.A., Barelli, L., Lazaroiu, G.: Real-time stochastic power management strategies in hybrid renewable energy systems: A review of key applications and perspectives. Electr. Power Syst. Res. 127(6), 106497 (2020).
19. Allouhi, A.: Solar PV integration in commercial buildings for self-consumption based on life-cycle economic/environmental multi-objective optimization. J. Clean Prod. 122375 (2020).
20. Hirose, T., Matsuo, H.: Standalone hybrid wind-solar power generation system applying dump power control without dump load. IEEE Trans. Ind. Electron. 59(2), 988–997 (2012).
21. Rahman, S.A., Vanderheide, T., Varma, R.K.: Generalised model of a photovoltaic panel. IET Renew. Power Gener. 8(3), 217–229 (2014).
22. Milocco, R.H., Thomas, J.E., Castro, B.E.: Generic dynamic model of rechargeable batteries. J. Power Sources 246, 609–620 (2014).
23. Cugnet, M., Liaw, B.Y.: Effect of discharge rate on charging a lead-acid battery simulated by mathematical model. J. Power Sources 196(7), 3414–3419 (2011).
24. Kim, J., Lee, J., Cho, B.H.: Equivalent circuit modeling of PEM fuel cell degradation combined with a LFRC. IEEE Trans. Ind. Electron. 60(11), 5086–5094 (2013).
25. Gyawali, N., Ohsawa, Y.: Integrating fuel cell/electrolyzer/ultracapacitor system into a stand-alone microhydroplant. IEEE Trans. Energy Convers. 25(4), 1092–1101 (2010).
26. Dispenza, G., Sergi, F., Napoli, G., Antonucci, V., Andaloro, L.: Evaluation of hydrogen production cost in different real case studies. J. Energy Storage 24(April), 100757 (2019).
27. Parida, A., Chatterjee, D.: Cost effective utility-solar photovoltaic based hybrid scheme for institutional buildings: A case study. IET Gener. Transm. Distrib. 11(5), 1102–1110 (2017).
28. Bastidas-Rodriguez, J.D., Franco, E., Petrone, G., Ramos-Paja, C.A., Spagnuolo, G.: Maximum power point tracking architectures for photovoltaic systems in mismatching conditions: A review. IET Power Electron 7(6), 1396–1413 (2014).
29. Kumar, N., Hussain, I., Singh, B., Panigrahi, B.K.: Self-adaptive incremental conductance algorithm for swift and ripple-free maximum power harvesting from PV array. IEEE Trans. Ind. Inform. 14(5), 2031–2041 (2018).
30. Sera, D., Mathe, L., Kerekes, T., Spataru, S.V., Teodorescu, R.: On the perturb-and-observe and incremental conductance mpppt methods for PV systems. IEEE J. Photovoltaics 3(3), 1070–1078 (2013).
31. Guillaud, X., Faruque, M.O., Teninge, A., et al.: Applications of real-time simulation technologies in power and energy systems. IEEE Power Energy Technol. Syst. J. 2(3), 103–115 (2015).
32. Kumar, M., Srivastava, S.C., Singh, S.N.: Control strategies of a DC microgrid for grid connected and islanded operations. IEEE Trans. Smart Grid 6(4), 1588–1601 (2015).
33. Naidu, B.R., Panda, G., Siano, P.: A self-reliant dc microgrid: Sizing, control, adaptive dynamic power management, and experimental analysis. IEEE Trans Ind. Inform. 14(8), 3300–3313 (2018).
34. Goli, P., Shireen, W.: PV integrated smart charging of PHEVs based on DC link voltage sensing. IEEE Trans. Smart Grid 5(3), 1421–1428 (2014).
35. Sandels, C., Widén, J., Nordström, L.: Forecasting household consumer electricity load profiles with a combined physical and behavioral approach. Appl. Energy 131, 267–278 (2014).

How to cite this article: Das V, Singh AK, Karuppanan P, Kumar P, Singh SN, Agelidis VG: Energy management and economic analysis of multiple energy storage systems in solar PV/PEMFC hybrid power systems. Energy Convers Econ. 2020;1:124–140. https://doi.org/10.1049/enc2.12011