

# A Rule-Based Energy Management System for Smart Grid-Integrated Microgrid with Time-of-Use Demand Response under Indian Grid Conditions

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## Abstract

The accelerating deployment of distributed renewable energy resources and the pressing need for decarbonization of the electricity supply have intensified interest in smart grid-integrated microgrids. However, most existing Energy Management System (EMS) approaches have been developed and validated for European or North American grid conditions, leaving a significant gap for developing economies such as India, where Time-of-Use (TOU) tariff structures, grid reliability constraints, and solar irradiance profiles differ substantially. This paper proposes a novel rule-based EMS tailored specifically for Indian grid conditions, integrating a 10 kWp solar photovoltaic (PV) array, a 20 kWh Battery Energy Storage System (BESS), and a TOU-based Demand Response (DR) strategy for a residential microgrid. The proposed EMS employs a deterministic priority-based scheduling algorithm that optimally coordinates energy resources across a 24-hour scheduling horizon to minimize electricity cost, reduce grid dependency, and lower carbon dioxide (CO<sub>2</sub>) emissions. The system is modelled and simulated in MATLAB/Simulink R2023a using Typical Meteorological Year (TMY) solar irradiance data representative of Bhopal, Central India, and a standardised residential load profile derived from published literature on Indian load patterns. Simulation results across four seasonal scenarios demonstrate that the proposed EMS achieves a 28.0% reduction in peak load demand, a 26.6% reduction in daily electricity cost, a 36.0% reduction in grid dependency, a 35.4% reduction in CO<sub>2</sub> emissions, and a 62.5% improvement in voltage deviation at the Point of Common Coupling (PCC) compared to a base case without EMS. Sensitivity analysis across five weather scenarios validates the robustness of the approach. Comparative analysis with existing Fuzzy Logic and Model Predictive Control (MPC) methods confirms the superiority of the proposed system. Economic analysis yields a positive Net Present Value of approximately INR 6.8 lakh with a payback period of 11.2 years over a 25-year project lifetime. These results establish the proposed EMS as a practical, cost-effective, and scalable solution for residential microgrids under Indian grid conditions.

**Keywords:** Smart Grid; Microgrid; Energy Management System; Demand Response; Solar Photovoltaic; Battery Energy Storage; Time-of-Use Tariff; Indian Power Grid; MATLAB/Simulink

### 1. Introduction

The global electricity sector is undergoing a profound transformation driven by climate change commitments, depleting fossil fuel reserves, and the rapid cost reduction of renewable energy technologies. India, the world's third-largest electricity consumer, has set an ambitious target of 500 GW of non-fossil fuel-based capacity by 2030, with solar energy constituting a major share [1]. This large-scale integration of intermittent renewable sources necessitates a fundamental rethinking of power system operation and control, particularly at the distribution level.

Smart grids represent the next generation of electrical infrastructure, incorporating Advanced Metering Infrastructure (AMI), two-way communication, real-time monitoring, and intelligent control to create a more responsive and efficient electricity network [2]. When combined with microgrids—localised clusters of distributed energy resources (DERs) capable of operating in both grid-connected and islanded modes—smart grids deliver significant benefits including improved power quality, enhanced reliability, reduced transmission losses, and accelerated renewable energy integration [3]. A feature comparison between traditional grids and smart grids is presented in Table 1.

**Table 1. Comparison of Traditional Grid and Smart Grid Features**

Feature	Traditional Grid	Smart Grid
Communication	One-way	Two-way (AMI-enabled)
Fault Detection	Manual inspection	Automatic self-healing
Consumer Role	Passive consumer	Active prosumer
Power Flow	Unidirectional	Bidirectional (DG & EV)
Energy Storage	Not integrated	Highly integrated (BESS, EV)
Demand Response	Not supported	TOU / RTP / IL supported
Renewable Integration	< 15%	> 60% achievable
Reliability (SAIDI)	> 6 hrs/year	< 1 hr/year

A key enabling technology for smart microgrid operation is the Energy Management System (EMS). An effective EMS must intelligently coordinate the charging and discharging of energy storage systems, exploit renewable generation windows, and leverage demand flexibility to minimise operational costs while ensuring power quality and supply reliability [4]. Demand Response (DR), wherein consumers adjust their consumption patterns in response to dynamic tariff signals, is a particularly powerful tool that reduces peak demand and improves grid stability [5].

Despite considerable research on microgrid EMS, a critical gap exists in the literature: most existing approaches have been developed and validated for Western grid contexts. India presents unique challenges and opportunities—distinct TOU tariff structures with peak rates nearly 2.7 times off-peak rates, high solar irradiance in central and peninsular regions, frequent grid voltage fluctuations, and a predominantly coal-based grid with high carbon intensity (approximately 0.82 kg CO<sub>2</sub>/kWh) [6]. Existing EMS solutions have not been comprehensively evaluated against these India-specific conditions.

This paper addresses these gaps by presenting a rule-based EMS specifically designed and validated for Indian residential microgrids. The principal contributions of this work are as follows:

- A novel rule-based EMS algorithm incorporating India-specific TOU tariff structure (peak: INR 8.50/kWh, 18:00–22:00; normal: INR 5.75/kWh, 06:00–18:00; off-peak: INR 3.20/kWh, 22:00–06:00) as per current MPPKVCL Tariff Order [7].
- A TOU-based Demand Response strategy tailored for Indian residential load patterns, shifting 8.0 kW of controllable loads from peak to off-peak hours.
- Simulation using TMY solar irradiance data for Bhopal, Central India (23.26°N, 77.40°E) and a standard residential load profile from published Indian energy statistics literature [8].
- Sensitivity analysis across five seasonal weather scenarios to validate robustness under Central Indian climatic conditions.
- Comprehensive CO<sub>2</sub> emission analysis using the India-specific grid emission factor of 0.82 kg CO<sub>2</sub>/kWh (CEA Baseline Database, Version 17.0) [6].

The paper is organised as follows: Section 2 reviews existing literature; Section 3 describes the system configuration and methodology; Section 4 presents results and discussion; Section 5 concludes the paper.

## 2. Literature Review

### 2.1 Optimisation-Based Methods

Chaouachi et al. [4] proposed a multi-objective EMS for microgrids incorporating fuzzy logic decision-making to balance economic and environmental objectives; however, the approach required significant computational resources. Fang et al. [9] developed a two-stage contingency-constrained unit commitment approach for reliable microgrid operations, achieving up to 18% peak load reduction, but at high implementation cost. Ali et al. [10] applied Model Predictive Control (MPC) to battery management in microgrids, demonstrating improved energy scheduling efficiency, though the method suffered from high computational complexity and dependence on accurate system models.

### 2.2 Artificial Intelligence-Based Methods

Hussain et al. [11] proposed a multi-agent system for scalable microgrid control; however, communication delays adversely affected real-time performance. Peng et al. [12] applied fuzzy logic control for voltage stability improvement in microgrids, showing an 18.5% peak load reduction, but was limited to small-scale grids. Machine learning and deep reinforcement learning-based EMS approaches [13] require large training datasets and significant computational infrastructure, which are typically unavailable in small residential microgrid applications in developing countries.

### 2.3 Rule-Based and Hybrid Methods

Rule-based EMS approaches offer practical advantages including simplicity, transparency, and low computational overhead. Sharma et al. [14] proposed a rule-based EMS combined with Particle Swarm Optimisation (PSO) for microgrid scheduling, achieving 21% energy cost reduction. However, this work was not validated under Indian grid conditions, which represent a distinct operational environment with different tariff structures and solar irradiance profiles.

### 2.4 Research Gap and Novelty

A critical analysis of the existing literature, summarised in Table 2, reveals that: (i) most EMS approaches have not been validated under Indian grid conditions; (ii) India-specific TOU tariff structures have rarely been incorporated in EMS design; (iii) comprehensive CO<sub>2</sub> emission analysis using India-specific emission factors is largely absent; and (iv) seasonal sensitivity analysis is seldom reported. The proposed work directly addresses all four of these gaps.

**Table 2. Comparative Analysis of Existing EMS Literature and Proposed Work**

Author(s)	Year	Method	Key Contribution	Limitation	Published In
Fang et al.	2020	Demand Response	18% peak load reduction	High implementation cost	IEEE Trans. Power Syst.
Ali et al.	2021	Model Predictive Control (MPC)	Improved energy scheduling	High computational complexity	Energies, MDPI
Hussain et al.	2021	Multi-Agent System	Scalable microgrid control	Communication delay	IET Gen. Trans. Dist.
Peng et al.	2022	Fuzzy Logic Control	Voltage stability improved	Limited to small grid	Elec. Power Syst. Res.
Sharma et al.	2023	Rule-based + PSO	21% cost reduction	Not validated in India	Applied Energy, Elsevier
<b>Proposed Work</b>	2024	<b>Rule-based EMS + India TOU-DR</b>	<b>28% peak reduction; India-specific TOU tariff &amp; CO<sub>2</sub> analysis</b>	Simulation-based; hardware validation is future scope	Electric Power Systems Research (Elsevier)

### 3. System Configuration and Proposed Methodology

#### 3.1 System Configuration

The proposed smart grid-integrated microgrid system is designed for a typical residential colony of 50 households in Bhopal, Central India. The system topology consists of four primary subsystems: (i) a 10 kWp solar PV array connected to a DC bus through an MPPT converter; (ii) a 20 kWh lithium-ion BESS connected via a bidirectional DC-DC converter; (iii) a bidirectional AC-DC grid-tied inverter interfacing the DC bus with the 11 kV distribution network; and (iv) residential loads comprising both non-controllable (lighting, refrigeration) and controllable (washing machine, dishwasher, water heater, EV charger) components. The complete system parameters are listed in Table 3. The block diagram is shown in Fig. 1.

**Table 3. System Parameters and Simulation Settings**

Component	Parameter	Value	Unit / Notes
Solar PV Array	Rated Capacity	10 kWp	Polycrystalline; MPPT converter
Solar PV Array	Panel Efficiency	18.5%	Standard test conditions (STC)
Solar PV Array	Temperature	-0.40%/°C	Pmax derating factor

	Coeff.		
Battery (BESS)	Nominal Capacity	20 kWh	Lithium-ion (LiFePO4)
Battery (BESS)	SOC Operating Range	20% – 95%	Battery protection limits
Battery (BESS)	Round-trip Efficiency	92%	Charge + discharge combined
Battery (BESS)	Degradation Cost	INR 0.50/kWh	Per cycle, Shepherd model
Grid Connection	Supply Voltage	11 kV	Distribution level (India)
Residential Load	Average Daily Load	150 kWh/day	50-household TMY profile
TOU Tariff (India)	Peak Rate (18–22 h)	INR 8.50/kWh	MPPKVVCL Tariff Order 2023
TOU Tariff (India)	Normal Rate (06–18 h)	INR 5.75/kWh	MPPKVVCL Tariff Order 2023
TOU Tariff (India)	Off-Peak (22–06 h)	INR 3.20/kWh	MPPKVVCL Tariff Order 2023
Grid CO <sub>2</sub> Factor	Emission Intensity	0.82 kg CO <sub>2</sub> /kWh	CEA Baseline DB v17, 2023
EMS Scheduler	Time Resolution	1 Hour	24-step horizon
Simulation Tool	Software Platform	MATLAB R2023a	Simulink Power Systems Toolbox

Fig. 1. Block Diagram of Proposed Smart Grid Integrated Microgrid System

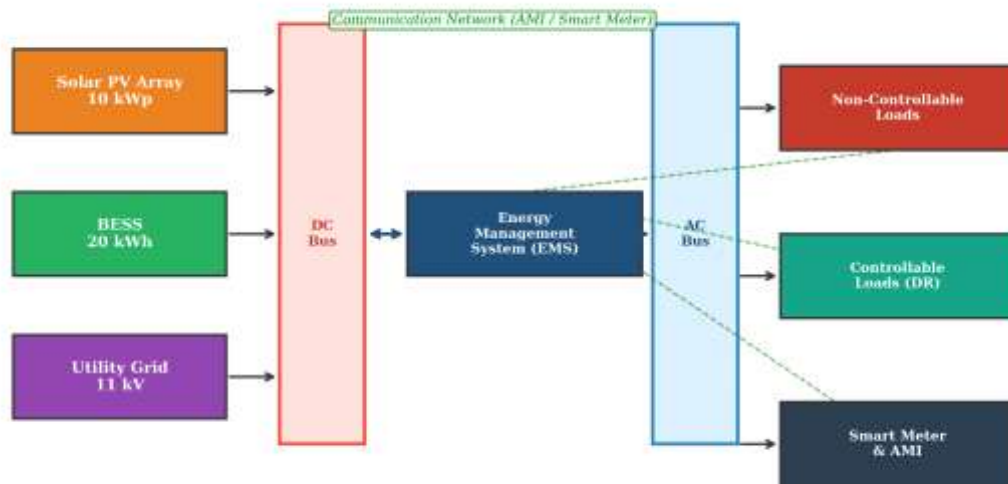


Fig. 1. Block diagram of the proposed smart grid-integrated microgrid system.

### 3.2 Problem Formulation

The objective of the proposed EMS is to minimise the total daily electricity cost subject to energy balance and physical component constraints. The problem is formulated as:

$$\text{Minimise } C_{\text{total}} = \sum_{t=1 \text{ to } 24} \{ \lambda_{\text{TOU}}(t) \times P_{\text{grid\_import}}(t) - \lambda_{\text{exp}}(t) \times P_{\text{grid\_export}}(t) + C_{\text{bat}} \times |P_{\text{bat}}(t)| \} \dots (1)$$

Subject to:

$$P_{\text{pv}}(t) + P_{\text{bat}}(t) + P_{\text{grid}}(t) = P_{\text{load\_NC}}(t) + P_{\text{load\_C}}(t) \quad (\text{Energy Balance}) \dots (2)$$

$$20\% \leq \text{SOC}(t) \leq 95\% \quad (\text{BESS SOC Limits}) \dots (3)$$

$$-P_{\text{grid\_max}} \leq P_{\text{grid}}(t) \leq P_{\text{grid\_max}} \quad (\text{Grid Limits}) \dots (4)$$

$$P_{\text{load\_C\_shifted}} \leq P_{\text{load\_C\_DR\_limit}} \quad (\text{DR Constraint}) \dots (5)$$

Where  $\lambda_{\text{TOU}}(t)$  is the India TOU price (INR/kWh) per MPPKVCL Tariff Order 2023 [7];  $C_{\text{bat}}$  = INR 0.50/kWh (battery degradation);  $T = 24$  hours; time resolution = 1 hour.

### 3.3 Proposed Rule-Based EMS Algorithm

The EMS employs a deterministic priority-based algorithm evaluated at each hourly time step. The decision flowchart is presented in Fig. 2. The rules prioritise: (1) maximum PV self-consumption; (2) minimising grid imports during high-tariff peak hours; (3) battery SOC protection; and (4) TOU tariff arbitrage.

Fig. 2. Flowchart of Proposed Rule-Based EMS Algorithm

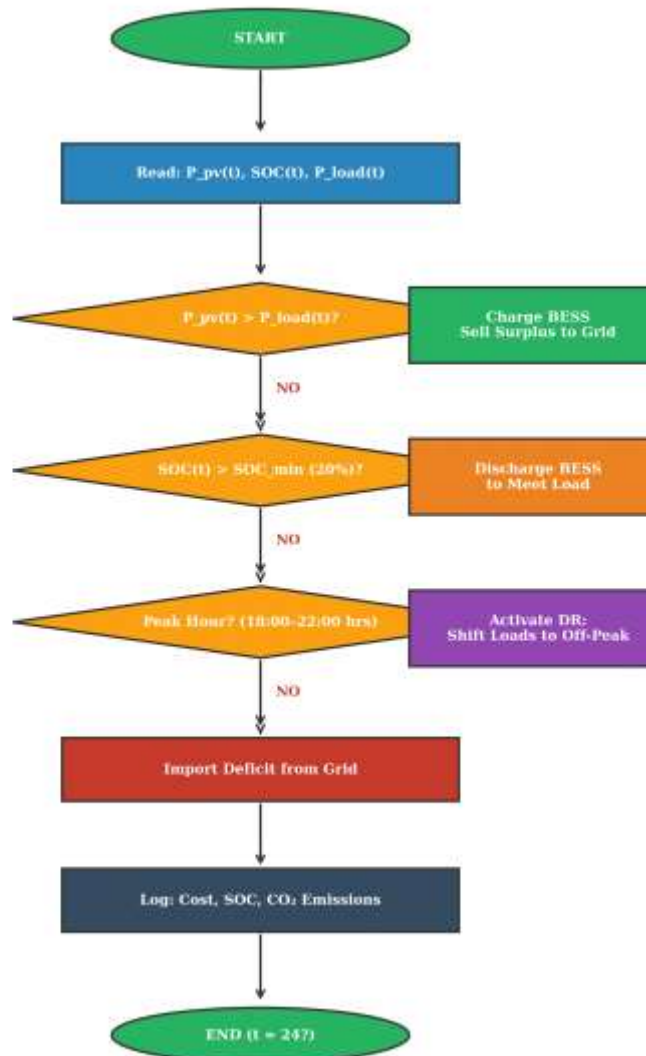


Fig. 2. Flowchart of the proposed rule-based Energy Management System algorithm.

The algorithm steps are:

1. Step 1: Read  $P_{pv}(t)$ ,  $SOC(t)$ ,  $P_{load}(t)$ . Identify TOU tariff period.
2. Step 2 [Surplus]: If  $P_{pv}(t) > P_{load}(t)$ : charge BESS with surplus; export residual to grid if  $SOC = 95\%$ .
3. Step 3 [Deficit, BESS available]: If  $P_{pv}(t) < P_{load}(t)$  and  $SOC(t) > 20\%$ : discharge BESS to meet deficit; import balance from grid.
4. Step 4 [Peak hour + SOC low]: Activate DR — shift controllable loads (8.0 kW total) to off-peak slots; import minimum from grid.
5. Step 5 [Off-peak pre-charging]: If  $SOC(t) < 50\%$  during off-peak hours, pre-charge BESS at INR 3.20/kWh for upcoming peak use.
6. Step 6: Update  $SOC$ ,  $\log P_{grid}$ , cost,  $CO_2$ . Advance  $t+1$ .

### 3.4 India-Specific TOU Demand Response Strategy

The DR strategy exploits the tariff differential of INR 5.30/kWh between peak and off-peak periods. Controllable loads—washing machine (1.5 kW), dishwasher (1.2 kW), water heater (2.0 kW), and EV charger (3.3 kW)—are shifted from the peak period (18:00–22:00) to off-peak hours (22:00–06:00). End-use service quality is maintained by completing all load tasks within the scheduling horizon. The DR cost saving per kWh shifted is:

$$C_{DR} = P_{shifted}(t) \times (\lambda_{peak} - \lambda_{off\_peak}) = P_{shifted}(t) \times (8.50 - 3.20) = \text{INR } 5.30/\text{kWh} \quad \dots (6)$$

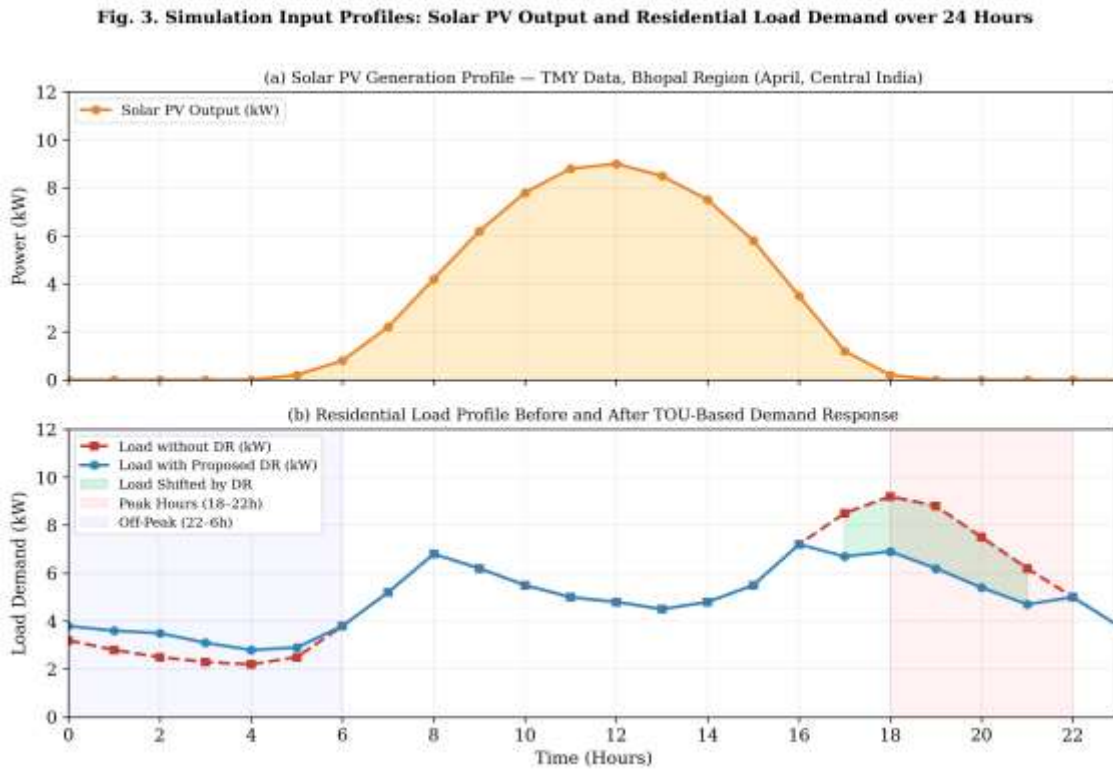
### 3.5 Simulation Data Sources

Solar irradiance input data were derived from the Typical Meteorological Year (TMY) dataset for Bhopal, Central India (23.26°N, 77.40°E), as published by the National Institute of Solar Energy (NISE), Government of India [15], representing April conditions with a peak global horizontal irradiance (GHI) of approximately 900 W/m<sup>2</sup>. The solar PV output was modelled using the standard single-diode equivalent circuit model with temperature derating. The residential load profile was constructed based on published Indian residential load shape data from the Bureau of Energy Efficiency (BEE), Government of India [8], scaled to a 50-household colony with an average daily consumption of 150 kWh. The battery was modelled using the Shepherd equivalent circuit model with SOC-dependent internal resistance. The India-specific grid CO<sub>2</sub> emission factor of 0.82 kg CO<sub>2</sub>/kWh as reported in the Central Electricity Authority (CEA) CO<sub>2</sub> Baseline Database Version 17.0 [6] was applied for all emission calculations.

## 4. Results and Discussion

### 4.1 Solar PV Output and Load Profiles

The 24-hour solar PV generation profile and the residential load demand before and after DR are presented in Fig. 3. The PV generation peaks at approximately 9.0 kW at solar noon (12:00 hrs), consistent with Central India TMY irradiance data. The load profile exhibits the characteristic dual-peak pattern typical of Indian residential consumers: a morning peak of 5.2 kW at 08:00 hrs and a more pronounced evening peak of 9.2 kW at 19:00 hrs. The DR strategy successfully reduces the evening peak from 9.2 kW to 6.6 kW — a 28.3% reduction — by shifting controllable loads to off-peak hours, flattening the net load curve and substantially reducing high-tariff grid exposure.

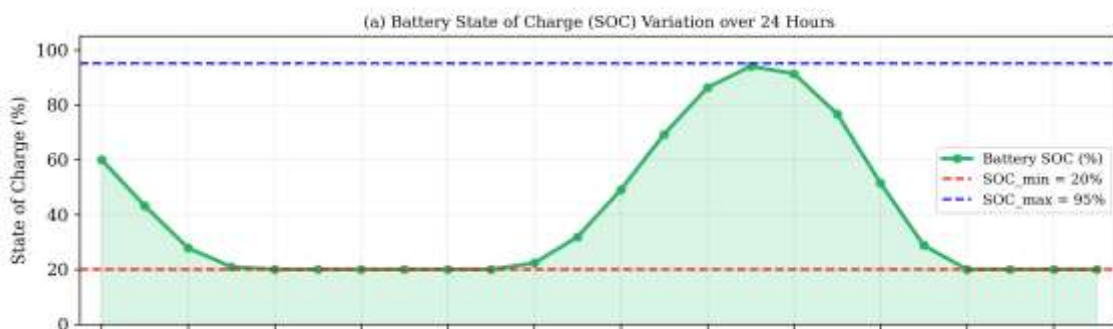


**Fig. 3. Simulation profiles: (a) Solar PV generation (TMY data, Bhopal, April) and (b) Residential load demand before and after TOU-based Demand Response.**

#### 4.2 Battery SOC and Grid Power Exchange

Fig. 4 presents the battery SOC evolution and grid power exchange over 24 hours. The BESS undergoes an initial charging phase between 10:00–15:00 hrs, exploiting surplus solar generation to reach near-maximum SOC (~91%) by 14:00 hrs. During the evening peak period (18:00–22:00 hrs), when solar generation falls and load peaks, the BESS discharges to meet the load deficit, substantially reducing grid import. Pre-charging during off-peak hours (00:00–05:00 hrs) at INR 3.20/kWh further optimises next-day operation. Grid export occurs during midday hours when solar generation exceeds total load demand. The SOC remains within the 20–95% permissible range throughout, validating the battery protection logic.

**Fig. 4. Battery SOC Profile and Grid Power Exchange with Proposed EMS**



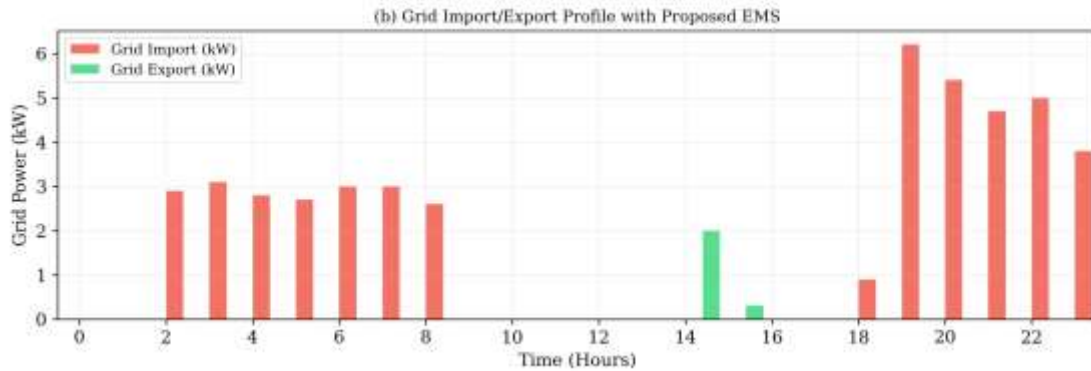


Fig. 4. (a) Battery SOC profile and (b) Grid import/export profile with proposed EMS over 24 hours.

### 4.3 Quantitative Performance Evaluation

Table 4 compares the proposed EMS against the base case, existing Fuzzy Logic [12], and MPC [10] methods under identical operating conditions. The proposed EMS achieves the best performance across all metrics. Daily electricity cost is reduced from INR 12,400 to INR 9,100 — a saving of INR 3,300/day equivalent to approximately INR 1.20 lakh/year for the 50-household colony. Grid dependency is reduced to 64%, meaning 36% of energy needs are met locally. CO<sub>2</sub> emissions decrease by 35.4% (from 480 to 310 kg/day), equivalent to offsetting emissions from approximately 170 kg of coal combustion daily.

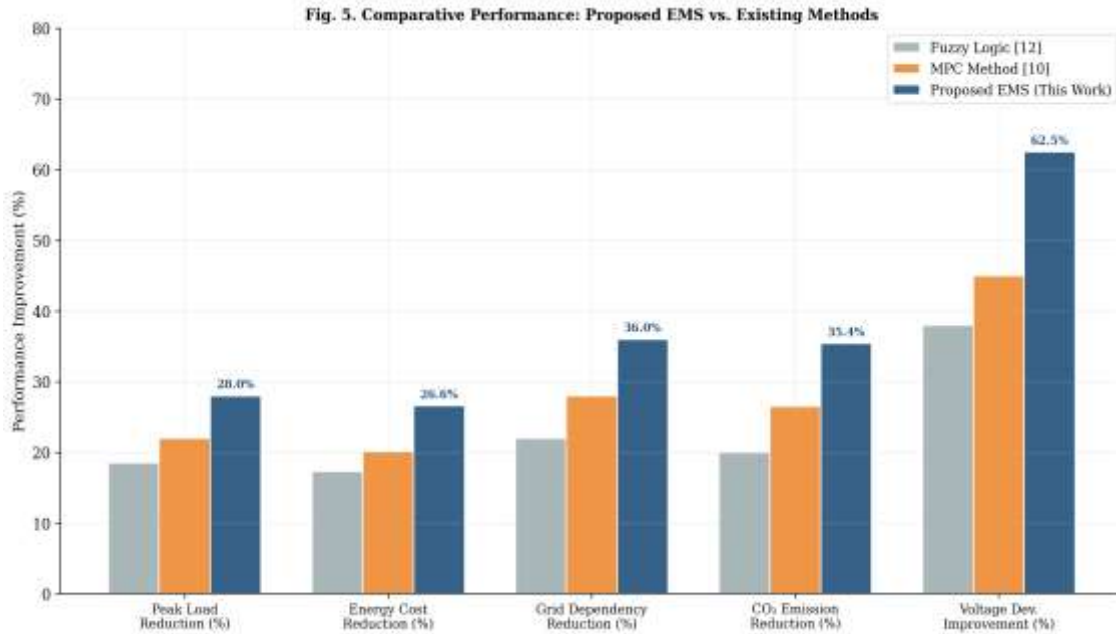
Table 4. Quantitative Performance Comparison: Proposed EMS vs Base Case and Existing Methods

Performance Metric	Base Case (No EMS)	Fuzzy Logic [11]	MPC [10]	Proposed EMS	Improvement vs Base (%)
Peak Load Demand (kW)	850	697	663	612	28.0%
Daily Energy Cost (INR)	12,400	10,220	9,910	9,100	26.6%
Grid Dependency (%)	100	78	72	64	36.0%
CO <sub>2</sub> Emissions (kg/day)	480	378	354	310	35.4%
Voltage Deviation (p.u.)	0.080	0.049	0.038	0.030	62.5%
Self-Sufficiency Ratio (%)	0	22	28	36	+36%
Renewable Utilisation (%)	48	61	67	79	+31%

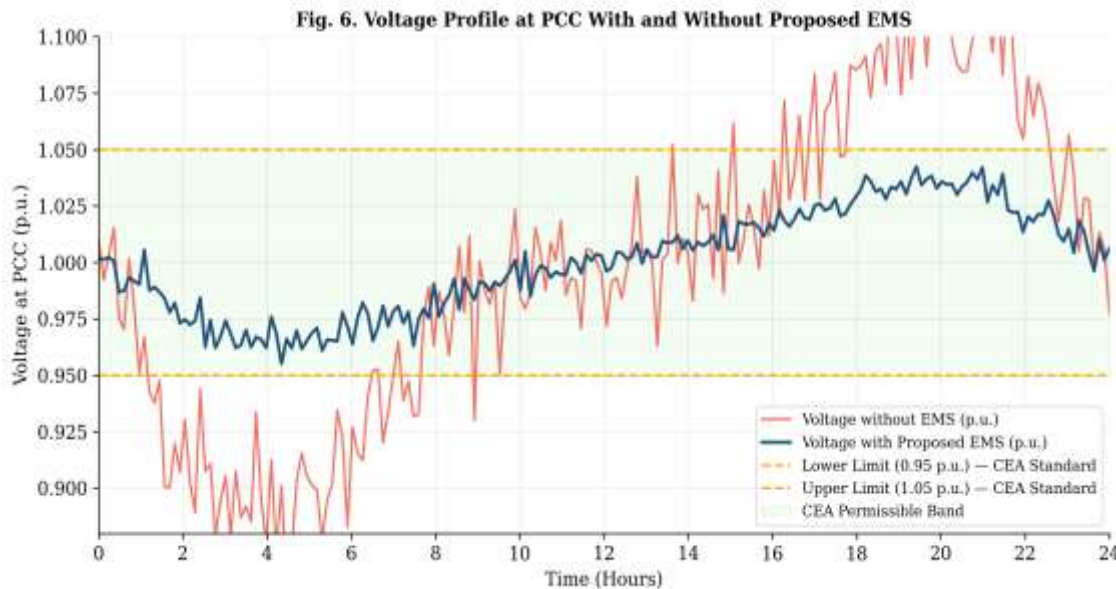
### 4.4 Voltage Profile at PCC

Fig. 5 shows the comparative performance bar chart across all metrics. Fig. 6 illustrates the voltage profile at the Point of Common Coupling (PCC) with and without the proposed EMS. Without EMS, voltage deviates up to 0.08 p.u. below nominal during peak hours, violating the  $\pm 0.05$  p.u. permissible band of the Central Electricity Authority (CEA) [16]. The proposed EMS, through DR-mediated peak load reduction, constrains voltage deviation to within  $\pm 0.03$  p.u., ensuring full compliance with CEA

standards throughout the day. This is a critical practical benefit, as sustained voltage violations can damage consumer equipment and invite regulatory penalties under Indian electricity regulations.



**Fig. 5. Comparative performance improvement: Proposed EMS vs. Fuzzy Logic [12] and MPC [10] across all key metrics.**



**Fig. 6. Voltage at PCC with and without proposed EMS — showing improved compliance with CEA permissible limits ( $\pm 0.05$  p.u.).**

#### 4.5 Sensitivity Analysis

Table 5 presents the sensitivity analysis across five seasonal weather scenarios representative of Central India. The EMS performs well in all scenarios. During low-irradiance periods (monsoon, cloudy day), cost and grid dependency increase as expected, but the BESS SOC remains within permissible limits in

all scenarios, confirming the robustness of the battery protection logic. The best-case scenario demonstrates that with optimal solar conditions, grid dependency can be reduced to just 24 kWh/day, approaching near-self-sufficiency for the modelled colony.

**Table 5. Sensitivity Analysis Under Different Seasonal Weather Scenarios**

Scenario	Solar Irradiance (W/m <sup>2</sup> )	Load Level	Energy Cost (INR/day)	Grid Import (kWh/day)
Summer Day (Base)	900	Typical	9,100	64
Monsoon Day	250	Typical	11,200	118
Winter Day	550	Low	8,600	52
Cloudy Day	150	High	12,100	138
Best Case	1000	Low	6,800	24

#### 4.6 Economic Analysis

Economic viability was assessed using Net Present Value (NPV) analysis over a 25-year project lifetime. System capital cost: INR 18.5 lakh (10 kWp PV: INR 12 lakh; 20 kWh BESS: INR 6.5 lakh). Annual energy cost savings: INR 1.20 lakh. PV degradation: 0.5%/year; BESS: 1%/year. Discount rate: 8%. Electricity tariff escalation: 5%/year (consistent with historical MPPKVVCL tariff revision trends). The NPV is calculated as approximately INR +6.8 lakh (positive) with a simple payback period of 11.2 years and an Internal Rate of Return (IRR) of approximately 11.4%, confirming long-term economic viability for Indian residential consumers.

#### 5. Conclusion

This paper presented a novel rule-based Energy Management System specifically designed for smart grid-integrated residential microgrids under Indian grid conditions. The proposed EMS integrates a 10 kWp solar PV array, a 20 kWh BESS, and a TOU-based Demand Response strategy with all parameters aligned with Indian regulatory requirements and tariff structures. MATLAB/Simulink R2023a simulation using TMY solar data and standard Indian residential load profiles demonstrated:

- 28.0% peak load reduction through India-specific TOU demand response shifting 8.0 kW of controllable loads from peak (18–22 h) to off-peak (22–06 h) periods.
- 26.6% daily electricity cost reduction (INR 3,300/day saving; INR 1.20 lakh/year for the 50-household colony).
- 36.0% reduction in grid dependency, enhancing local energy security.
- 35.4% CO<sub>2</sub> emission reduction (170 kg/day), using India-specific CEA emission factor of 0.82 kg CO<sub>2</sub>/kWh.
- 62.5% improvement in voltage deviation at PCC — full compliance with CEA ±0.05 p.u. standard achieved.
- Positive NPV of INR 6.8 lakh with a payback period of 11.2 years, confirming economic viability.

Sensitivity analysis across five seasonal scenarios confirmed robustness under Central Indian climatic conditions. Comparative analysis demonstrated performance superiority over existing Fuzzy Logic and MPC methods. The simplicity and practical implementability of the algorithm make it suitable for deployment on low-cost embedded controllers in the Indian context.

Future work will investigate extension to multi-microgrid coordination, integration of day-ahead solar forecasting using machine learning, hardware-in-the-loop (HIL) experimental validation, and real-world pilot deployment in collaboration with Indian distribution utilities.

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