© APR 2026 | IRE Journals | Volume 9 Issue 10 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I10-1715825

Energy Management System for Mini-grid

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Abstract- This review paper provides a comprehensive analysis of Energy Management Systems (EMS) for mini-grid systems, focusing on their role in enhancing system efficiency, reliability, and cost-effectiveness in remote or decentralized settings. It explores the challenges of managing intermittent renewable energy sources—such as photovoltaic (PV) and wind—alongside battery energy storage systems (BESS) and backup generators. To this end, the paper critically examines hierarchical, centralized, and decentralized control strategies for balancing demand and supply. The paper also compares methodologies for optimizing energy flow, including classical programming, metaheuristic techniques, and artificial intelligence (AI) approaches. The paper also reviews demand-side management (DSM), load forecasting, and demand response programs to improve operational efficiency. The review concludes that advanced EMS, specifically those leveraging AI and predictive control, are critical for accelerating the transition to renewable-based, sustainable mini-grids.

Index Terms- Mini-grid, Centralized control, Decentralized Control, state of charge (SOC), Smart Meters / IoT, Demand Side Management (DSM)

I. INTRODUCTION

1.1 Background

A mini-grid, also sometimes referred to as a "micro grid or isolated grid", is essentially a set of small-scale electricity generators interconnected to a distribution network that supplies electricity to a small, localized group of customers (from 10 kW to 10 MW) [1, 2]. It usually operates independently from the national transmission grid.It typically includes a power generation source (such as solar panels, wind turbines, hydropower, or diesel generators), a distribution network (wires and poles), and a control system to manage the flow of electricity. The size and capacity of a mini-grid are determined by the energy demand of the community it serves.

A mini-grid typically comprises three core components [3]:

1. Generation Source: Solar panels, wind turbines, micro-hydro stations, or diesel generators.
2. Energy Storage: Batteries (primarily lithium-ion) to provide power during periods of low generation.
3. Distribution Network: Low-voltage wires and poles that deliver electricity directly to households and businesses.

Mini-grids are essential for reaching the nearly 600 million people in Sub-Saharan Africa who lack electricity [4]. Their importance lies in [5]:

1. Cost-Effectiveness: They avoid the prohibitive upfront costs of extending national transmission lines to sparsely populated or topographically challenging remote areas.
2. Reliability: Mini-grids can achieve 99% uptime, significantly higher than many national grids in developing regions, which may be operational less than half the time.
3. Productive Use of Energy (PUE): Unlike small solar home systems, mini-grids provide enough power for income-generating activities, such as irrigation pumps, agricultural processing (milling/drying), and refrigeration for small shops.
4. Social Impact: They power critical infrastructure like health clinics (for vaccine refrigeration) and schools, leading to improved healthcare delivery and educational outcomes.

There is a significant transition from traditional diesel-only mini-grids toward Hybrid Renewable Energy Systems (HRES), which combine multiple energy sources (e.g., solar + wind + battery or solar + diesel). This shift is driven by [6]:

1. Reliability & Resilience: Hybrids mitigate the intermittency of single renewable sources (e.g., solar not working at night) by integrating storage or backup generators.
2. Economic Viability: While 100% renewable systems are ideal, hybrids (often solar + diesel) are currently more financially attractive. They reduce fuel costs by 75–99% compared to diesel-only systems while maintaining a lower initial capital requirement than massive battery-only storage.
3. Environmental Goals: Moving to hybrids helps achieve SDG 7 (Clean Energy) by drastically reducing carbon emissions (e.g., a single PV-wind hybrid can reduce CO_2 by ~22.7 tons annually).
4. Technological Advancements: The declining cost of lithium-ion batteries and solar PV modules has made hybridizing existing diesel grids a "prime candidate" for modernization.

1.2 The Problem

The stochastic, intermittent, and unpredictable nature of renewable energy sources (solar/wind) combined with fluctuating load demand, creates significant grid stability challenges, including voltage/frequency fluctuations and supply-demand mismatches. To maintain stability and increase efficiency, an advanced Energy Management System (AEMS) is required to manage these uncertainties through real-time monitoring, forecasting, and optimization [7].

1.3 Role of Advanced Energy Management Systems (AEMS)

An AEMS functions as the "brain" of the energy system, coordinating generation, storage (BESS), and consumption to ensure efficient, safe, and cost-effective operations. The following are some functions of AEMS [8]:

1. Uncertainty Management: AEMS uses probabilistic scenario generation and forecasting tools (e.g., Deep Convolutional GANs) to anticipate variations in generation and load, reducing reliance on emergency power sources.
2. Optimal Dispatch & Control: AEMS uses advanced optimization algorithms (such as Model Predictive Control) to determine the best actions for charging/discharging batteries, managing conventional generation, and optimizing grid power, which can lead to 15–20% energy savings.
3. Stability Enhancement: AEMS can manage "effective" inertia in real-time, decreasing the cost of inertia management by up to 40%.
4. Reducing Curtailment: Advanced strategies, including demand response, minimize the amount of renewable energy that must be wasted (curtailed) due to network constraints.

The following are some benefits of AEMS:

1. Efficiency & Economy: AEMS optimizes the scheduling of units, reducing total daily operating costs for hybrid renewable systems.
2. Enhanced Resilience: AEMS can develop automated restoration plans in under 10 seconds for large areas.
3. Sustainability: By enabling higher penetration of renewables (up to 80%), AEMS contributes to reducing overall grid emissions [9].

The rest of this paper reviews the components and architecture of mini-grid systems. It then looks at the theory and design criteria of energy management systems for mini-grid systems.

II. MINI-GRID COMPONENTS AND SYSTEM ARCHITECTURE

2.1. Generation Sources

A hybrid power system utilizing solar PV, wind turbines, biomass, small hydro, and diesel generators combines renewable sources with conventional backup for reliable, cost-effective electricity, particularly in remote areas. This combination balances intermittent renewable output—like solar and wind—with stable baseload from biomass, hydro, and dispatchable diesel generators, often managed by battery storage.

Generation sources include the following:

1. Solar PV (Photovoltaic): Converts sunlight into electricity, typically used in solar-wind hybrid systems to provide daily power [10].
2. Wind Turbines: Generate electricity from kinetic energy, often paired with solar, as they can complement each other's intermittent nature [10].
3. Small Hydro: Typically utilizes run-of-river technology to generate consistent power from flowing water, offering high efficiency and low, stable costs [10].
4. Biomass: Converts organic materials (waste/wood) into renewable energy, providing consistent, dispatchable power that complements solar and wind [10].
5. Diesel Generators: Provide essential standby or peak-load capacity in hybrid systems, ensuring reliability when renewable sources are insufficient, though they have high operating costs [11].

Benefits of a hybrid system include the following [12]:

1. Reliability: Diesel ensures power when renewable sources are low.
2. Cost Efficiency: While initial setup can be high, using hybrid systems often provides a lower cost of energy (COE) than relying solely on diesel generators in remote areas.
3. Sustainability: Reduces reliance on fossil fuels, with potential for significantly lower carbon emissions compared to pure diesel generators.

2.2 Energy Storage Systems (ESS)

Energy Storage Systems (ESS) are critical for managing the intermittency of renewable energy, grid stabilization, and power backup. Key technologies include established electrochemical batteries (Lead-acid, Li-ion) and mechanical flywheel systems, each with distinct performance, cost, and lifespan characteristics [13, 14].

2.2.1. Battery Types

Lead-Acid Batteries

Lead-acid batteries are a mature technology commonly used for off-grid power systems, Uninterruptible Power Supplies (UPS), and emergency backup. They have the following characteristics [15, 16]:

1. Pros: Low capital cost (100 – 500 $/kWh), high reliability, and exceptional recyclability (>95% recycling rate).
2. Cons: Low energy density (25–35 Wh/kg), short cycle life (500–3,000 cycles), and susceptibility to degradation from deep discharges.
3. Variants: Vented (flooded) cells require maintenance, while Valve Regulated Lead-Acid (VRLA), such as AGM (Absorbent Glass Mat) and Gel designs, are maintenance-free and can operate in any position.
4. Advancements: Lead-carbon batteries improve upon traditional types by offering higher energy density and longer cycle life.

Lithium-ion (Li-ion) Batteries

Li-ion batteries are the dominant technology for both mobile applications and stationary grid storage due to their superior performance [13]. They have the following characteristics [17]:

1. Pros: High energy density (200–400 Wh/L), long cycle life (>10,000 cycles), and high round-trip efficiency (approx. 90-95%).
2. Cons: Higher initial capital costs, sensitivity to deep discharge and high temperatures, and safety concerns (fire risks) requiring a Battery Management System (BMS).
3. Dominant Chemistries: Lithium Iron Phosphate (LFP) is popular for stationary storage due to high safety and long life, while Nickel Manganese Cobalt (NMC) is favoured for high density.
4. Applications: Residential, commercial/industrial (C&I), and grid-scale storage.

2.2.2. Flywheel Energy Storage System (FESS)

Flywheel storage is a mechanical, non-chemical technology that stores electricity in the form of rotational kinetic energy. It has the following characteristics [18, 19]:

1. Key Characteristics: Flywheels consist of a massive rotor that spins at very high speeds in a vacuum chamber, coupled with a motor/generator to convert electrical energy to rotational energy and vice versa.
2. Advantages: Almost infinite cycle life, very fast response times (milliseconds), and efficiency that is independent of depth of discharge.
3. Best Use Cases: High-power applications requiring frequent, short-duration cycling, such as frequency regulation and power quality stabilization, rather than long-duration energy storage.

2.2.3. Comparison Summary

Table 2.1 presents the comparison summary of the three energy storage technologies described so far.Table 2.1: Comparison summary of Lead-acid, Lithium-ion, and Flywheel energy storage.

Feature	Lead-Acid	Lithium-ion	Flywheel
Energy Density	Low	High	Low
Cycle Life	Low-Medium	High	Very High
Cost	Low	High	High
Response Time	Fast	Very Fast	Instant
Main Use Case	Backup/Small PV	Grid/Residential	Frequency Regulation

2.3. Mini-Grid Architectures

Mini-grid architectures are primarily categorized by how solar PV and battery storage are coupled—AC-coupled or DC-coupled—which determines the path electricity takes from generation to storage or consumption. DC-coupled systems are typically more efficient and cost-effective for new, small-to-medium off-grid projects, while AC-coupled systems offer superior flexibility and efficiency for large-scale, grid-tied or retrofitted systems [20].

2.3.1. AC-Coupled Architectures

In an AC-coupled system, solar PV and battery storage are independent, with both connected via their own inverters to the AC distribution bus. It has the following characteristics [20]:

1. How it works: Solar panels (DC) → PV Inverter (AC) → AC Grid → Battery Charger (DC) → Battery.
2. Best Use Cases: Retrofitting existing grid-tied solar systems; large-scale systems (above 8kW).
3. Advantages:
   i. High Scalability: Easy to expand by adding more solar PV or battery storage independently.
   ii. Flexibility: Can use different brands of inverters and batteries.
   iii. Retrofit Friendly: Ideal for adding batteries to systems with existing, functioning inverters.
4. Disadvantages:
   i. Lower Efficiency: Multiple conversions (DC → AC → DC → AC) can lead to 5–10% higher energy losses than DC systems.
   ii. Higher Cost: Requires two separate inverters (one for solar, one for battery).
   iii. Limited Off-Grid Ability: Less suited for very small, remote setups.

2.3.2. DC-Coupled Architectures

i. In a DC-coupled system, solar panels are connected directly to batteries via a charge controller (or a hybrid inverter) on the DC side before being inverted to AC for consumer use. It has the following characteristics [20]:

1. How it works: Solar panels (DC) → Charge Controller → Battery (DC) → Inverter → AC loads.

2. Best Use Cases: New off-grid installations; small-scale rural electrification; systems requiring maximum efficiency.
3. Advantages:

   i. Higher Efficiency: Direct DC-to-DC charging reduces conversion losses, with round-trip efficiency up to 98%.
   ii. Lower Cost: Often requires only one hybrid inverter for both solar and battery.
   iii. Better Off-Grid Performance: Ideal for remote locations, enabling black start capabilities.
   iv. Superior Low-Light Charging: Charge controllers can be more efficient than inverters in low sunlight.
4. Disadvantages [21]:

   i. Less Flexible: Harder to expand or mix different, already installed components.
   ii. Inverter Limitation: System power output is restricted to the maximum rating of the single inverter.

2.3.3. Head-to-Head Comparison

Table 2.2 presents a head-to-head comparison of the AC-coupled system versus the DC-coupled system.
Table 2.2: Comparison of AC-coupled system versus DC-coupled system [22].

Feature	AC-Coupled System	DC-Coupled System
Primary Use	Retrofits & Large Scale	New Installs & Off-Grid
Round-Trip Efficiency	90-94%	95-98%
Components	Solar + Battery Inverters	Single Hybrid Inverter
Cost	Higher (two inverters)	Lower (one inverter)
Flexibility	High (Modular)	Low (Integrated)
Main Advantage	Ease of expansion	Efficiency (fewer losses)

Key Considerations for Decision [21]:

1. New or Retrofit: If you have an existing solar system, AC coupling is usually easier. If starting fresh, DC is generally better.
2. Off-Grid vs. Grid-Tied: For maximum efficiency in remote, off-grid scenarios, DC-coupling is often preferred to maximize energy storage.
3. Loads: If the majority of power is used during the day (e.g., AC air conditioning), AC coupling is slightly more efficient. If power is mainly stored for night use, DC coupling is better.
4. System Size: Very large systems often use AC coupling, while small to medium-sized mini-grids often find higher performance with DC-coupled architectures.

2.4 Topology

Mini-grid control structures determine how generation sources, storage units, and loads are managed, influencing system reliability, efficiency, and computational complexity. The three primary approaches—centralized, decentralized, and distributed—differ in their use of communication, dependency on a single controller, and speed of response [23].

2.4.1. Centralized Control

In a centralized control structure, a single, central entity—typically a Microgrid Central Controller (MGCC)—collects data from all Distributed Energy Resources (DERs) and loads to make optimization decisions. It has the following characteristics [24]:

1. Key Features: High reliance on continuous communication links; single-point-of-failure risk.
2. Advantages:
   i. Global Optimization: Efficiently performs unit commitment and economic dispatch, resulting in optimal operation.
   ii. Simplified Management: Easier implementation of security policies and updates.
3. Disadvantages:

   i. Bottlenecks: High computational cost, which may cause latency as the number of nodes increases.
   ii. Vulnerability: A failure in the central controller can disable the entire microgrid.
4. Application: Suited for small-scale microgrids with a single owner where common goals are shared.

2.4.2. Decentralized Control

Decentralized control operates without a central controller. Instead, each DER or local agent operates independently, usually relying on local measurements (e.g., voltage and frequency) to take action [24]. It has the following characteristics [25]:

1. Key Features: No, or very limited, communication between controllers; "plug-and-play" capability.
2. Advantages:
   - High Reliability: The absence of a central point of failure increases system resilience.
   - Scalability: Easy to expand by adding new components without complex reconfiguration.
3. Disadvantages:
   - Sub-optimal Performance: Local nodes may conflict, leading to slower convergence toward system-wide objectives.
   - Lack of Global View: Difficult to achieve overall system optimization.
4. Application: Ideal for large, rapidly changing, or multi-owner systems (e.g., residential solar panels on a microgrid).

2.4.3. Distributed Control

Distributed control is a hybrid approach where local controllers make decisions based on local measurements and limited information exchange with neighbouring units. It has the following characteristics [23]:

1. Key Features: Peer-to-peer communication replaces the master-slave structure.
2. Advantages:
   i. Resilience & Flexibility: Retains functionality even if some communication links fail.
   ii. Balanced Performance: Faster response than centralized, but more coordinated than fully decentralized.

3. Disadvantages:
   i. Control Oscillation: Potential for stability issues during the convergence process.
   ii. Complexity: Designing coordination algorithms for communication networks can be complex.
4. Application: Modern, smart microgrids looking for both high resilience and good performance.

2.4.4. Summary Comparison

Table 2.3 presents a comparison of the different Mini-grid control structures.

Table 2.3: Comparison of AC-coupled system versus DC-coupled system [26].

Feature	Centralized	Decentralized	Distributed
Control Entity	Single (MGCC)	Local Nodes	Local + Neighbor
Communication	High (All-to-one)	None/Low (Local)	Limited (Neighbor-to-neighbor)
Resilience	Low (Single failure)	High (Very robust)	High (Flexible)
Computational Load	Very High	Very Low	Moderate
Response Speed	Slowest	Fastest	Fast
Plug-and-play	Low	High	Medium
Optimality	Global Optimal	Sub-optimal	Near Optimal

2.4.5. Key Differences and Trends

1. Grid Evolution: The industry is moving from traditional centralized structures to more decentralized and distributed models to better handle the intermittency of renewable energy sources and improve resilience [27].
2. Communication: Decentralized approaches are best for environments where communication infrastructure is expensive or unreliable, whereas distributed methods use sparse communication for better coordination [27].
3. Scalability: Decentralized systems handle increasing DERs better than centralized systems [27].

III. EMS FUNCTIONALITIES AND OBJECTIVES

3.1. Primary Functions

Mini-grid systems, particularly those utilizing renewable energy in rural or isolated areas, require sophisticated control mechanisms to ensure stability, reliability, and cost-effectiveness. Key operational areas include active power balancing, intelligent load shedding, frequency and voltage regulation, and battery State of Charge (SOC) optimization, all of which are aimed at maintaining system integrity. This is achieved in both grid-connected and islanded modes [28].

3.1.1. Power Balancing and Energy Management

The following are the key components of power balancing and energy management [29, 30]:

1. Balancing Generation and Demand: In isolated (islanded) mode, the mini-grid must balance generation and load in real-time, relying on Distributed Generation (DG) such as solar PV, wind, and diesel generators, alongside Battery Energy Storage Systems (BESS).
2. Intelligent Controllers: Intelligent Automatic Control Systems (ACS) use decentralized algorithms to manage load dispatching, emergency control, and power flow.
3. Storage and Demand Management: Battery storage plays a critical role in balancing load, while demand-side management (DSM)—such as shifting productive loads (e.g., grain mills) to daytime—reduces peak demand and lowers the levelized cost of electricity (LCOE) by up to 23%.

3.1.2. Load Shedding Strategies

The following are the key load shedding strategies [31, 32]:

1. Maintaining Stability: Load shedding is a critical, last-resort mechanism in isolated microgrids to prevent total blackout during disturbances.
2. Prioritization: Non-critical loads (e.g., residential) are typically curtailed first, while critical loads (e.g., community centres) are protected.
3. Optimization Techniques: Modern systems use techniques such as Particle Swarm Optimization (PSO) or mixed-integer linear programming (MILP) to minimize the amount of load shed while restoring stability.
4. Frequency-Based Shedding: Under-frequency load shedding (UFLS) is used, where load is shed when the frequency drops below a specific threshold.

3.1.3. Frequency and Voltage Control

The following are the key aspects of frequency and voltage control [33]:

Voltage Control (Reactive Power Management): Voltage variation occurs due to load changes; it is managed by controlling reactive power, using devices like capacitors or inverter-based VAR compensators to keep voltage within allowable limits (±5-6%).

1. Frequency Control (Active Power Balance): In islanded mode, battery inverters or generators often act as grid-forming units, using "droop control" to adjust power output and stabilize frequency.
2. Inverter-Based Control: Grid-forming inverters (GFM) set the frequency and

voltage, while grid-following inverters (GFL) track the voltage and frequency references.

3.1.4. Battery Management and SOC Optimisation

The following are the key aspects of battery management and SOC optimisation [34, 35]:

1. SOC Optimization: Optimization algorithms manage battery State of Charge (SOC) to prolong battery life and ensure capacity for nightly operations.
2. Bidirectional Flow: Battery inverters regulate DC link voltage and enable bidirectional flow for charging during excess generation and discharging during deficits.
3. Capacity Management: Battery storage helps mitigate the intermittency of renewable energy, often using a maximum Depth of Discharge (DOD) of around 70% to maintain health.
4. Hybrid Storage: Some advanced models incorporate hybrid systems (e.g., supercapacitors, hydrogen) to improve longevity and resilience.

3.1.5. Summary of Key Techniques

1. Hierarchical Control: Involves primary (local control), secondary (restoring voltage/frequency), and tertiary (economic optimization) levels [33].
2. Optimal Sizing: Using tools like HOMER Pro to minimize net present cost (NPC) while maintaining reliability [33].
3. Protection: In DC mini-grids, protection is more complex due to the lack of zero-crossing points, requiring specialized components [33].

3.2. Operational Objectives

Operational objectives focused on cost reduction (OPEX/CAPEX), emissions reduction, maximizing renewable penetration, and improving reliability require an integrated, technology-driven approach. Key strategies involve leveraging smart grid technologies, enhancing energy storage, adopting predictive maintenance, and optimizing hybrid power systems [36].

3.2.1. Cost Reduction (OPEX/CAPEX)

Cost reduction in both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) is crucial for improving net income, increasing efficiency, and managing cash flow. CAPEX involves upfront investments in long-term assets that are depreciated over time, while OPEX represents ongoing, day-to-day costs that are expensed immediately.

Key strategies for cost reduction across both categories include [37]:

1. Preventive & Predictive Maintenance: Shifting from reactive to condition-based maintenance using AI and IoT reduces unplanned downtime and repair costs.
2. Operational Efficiency: Optimizing asset performance—such as cleaning heat exchangers, reducing blower failure, and improving turbine blade efficiency—can lower operating costs and reduce fuel consumption.
3. Strategic Sourcing and Design: Streamlining procurement, optimizing site selection, and using standardized components can significantly lower capital expenditures (CAPEX).
4. Automation & Digitalization: Implementing digital energy management systems provides real-time data to optimize consumption and decrease energy procurement costs.

3.2.2. Emissions Reduction

Energy Management Systems (EMS) reduce emissions by optimizing energy use, cutting greenhouse gases, and automating efficiency.

Key ways EMS reduces emissions include [38]:

1. Renewable Energy Integration: Replacing fossil fuel-based generation with solar, wind, and storage reduces greenhouse gas emissions.
2. Energy Efficiency Measures: Transitioning to high-efficiency motors, pumps, and compressors directly reduces fuel combustion, particularly in industrial sectors.

3. Hybrid Systems: Utilizing combined heat and power (CHP) systems paired with renewables enables lower-carbon operations.

3.2.3. Maximizing Renewable Penetration

Maximizing renewable penetration involves integrating high shares of variable renewable energy (VRE) into the grid while ensuring stability, reducing costs, and limiting curtailment. Key strategies include utilizing energy storage systems (e.g., batteries), demand-side management (DSM), enhancing transmission capacities, and employing advanced forecasting to manage intermittent generation [39].

Key strategies for maximizing renewable penetration include [40]:

1. Energy Storage Systems (ESS): Utilizing batteries and pumped hydro to store excess renewable energy allows it to be used during peak demand, managing intermittent output.
2. Grid Modernization: Employing smart grids with advanced, two-way communication and automated control systems accommodates distributed energy resources (DERs).
3. Flexible Generation: Integrating synchronous condensers and flexible AC transmission systems (FACTS) provides stability, enabling higher, safer levels of variable renewable inputs.

3.2.4. Improving Reliability

Energy Management Systems (EMS) improve reliability by providing real-time monitoring, AI-driven predictive maintenance, and optimized control of distributed energy resources, reducing unplanned downtime by up to 75%. These systems enable automated load balancing, fault detection, and seamless integration of renewable sources to maintain grid stability and prevent overloading [41].

Key ways EMS improves reliability include [42]:

1. Condition-Based Monitoring: Real-time data monitoring allows for early detection of potential failures (e.g., compressor outages, turbine vibration), reducing downtime.
2. Asset Performance Management: Regularly monitoring and maintaining critical assets like boilers and heaters minimizes interruptions.
3. Hybrid Power Systems: Combining multiple renewable sources (e.g., solar + wind + hydro) ensures a more constant, reliable energy supply compared to a single source.
4. Grid Resilience: Utilizing microgrids and automated switching enhances, allowing for faster power restoration after disturbances.

Table 3.1 presents a summary of reliability improvement strategies.

Table 3.1: Summary of reliability improvement strategies.

Objective	Key Strategy
Cost Reduction	Predictive maintenance, AI optimization, and lowering CAPEX through standard design
Emissions Reduction	Transitioning to solar/wind, upgrading to efficient motors, and waste heat recovery
Renewable Penetration	Battery storage systems (BESS), smart grids, and flexible transmission
Reliability	Condition-based maintenance, hybrid energy sourcing, and automated grid monitoring

IV. FORECASTING TECHNIQUES

Short-term load and renewable energy forecasting (up to one week) uses

AI-driven models—specifically LSTM, ANN, and hybrid algorithms—combined with meteorological data to manage grid volatility. Techniques like Support Vector Machines (SVM) and Random Forest (RF) provide accurate, non-linear predictions for electricity demand and intermittent renewable generation [43].

Short-Term Load Forecasting (STLF) techniques include [43, 44]:

1. AI and Machine Learning: Artificial Neural Networks (ANN), Recurrent Neural Networks (RNN), and particularly Long Short-Term

Memory (LSTM) networks excel in handling non-linear load patterns.

2. Hybrid Models: Combining models, such as FFNN, with optimization algorithms, enhances accuracy, often reducing errors to a Mean Absolute Percentage Error (MAPE) of ~1.5%.
3. Conventional Statistical Methods: Autoregressive Integrated Moving Average (ARIMA) and Exponential Smoothing (ES) remain relevant for their simplicity and reliability when dealing with stable data [46].
4. Key Inputs: Data points such as hourly load demand, daily weather conditions (temperature, humidity), and scheduling [45].

Renewable Energy Production Forecasting techniques include [46]:

1. Wind/Solar Forecasting: Similar to load forecasting, deep learning models like LSTM-RNN and CNN are used to process time-series data to predict intermittent generation.
2. Weather-Dependent Parameters: Crucial inputs include solar radiation, wind speed, cloud cover, and cloud direction [47].
3. Optimization Algorithms: Techniques such as Gradient Boosting Regression Trees (GBRT) or TPE algorithms improve accuracy for high-speed wind generation [48].

The following are Key Trends & Parameters [44]:

1. Data Sources: Smart meters and sensors have increased data availability.
2. Accuracy Metrics: Evaluations often use RMSE (Root Mean Square Error) and MAE (Mean Absolute Error) to refine models [49].
3. Importance: These methods are vital for managing grid stability, preventing overloads, and enhancing energy security [50].

V. CLASSIFICATION OF ENERGY MANAGEMENT STRATEGIES

5.1 Conventional/Rule-Based Strategies

Energy Management Strategies (EMS) for mini-grids, particularly conventional and rule-based approaches, are designed to ensure system stability, maximize renewable energy usage, and extend battery life by managing power flow between generation, storage, and loads. These methods are favoured for their simplicity, real-time capability, and low computational requirements compared to optimization techniques [51].

5.1.1. Rule-Based Energy Management Strategies (RB-EMS)

Rule-based strategies use a set of predefined logic (often "If-Then-Else" statements) to manage the power flow in the mini-grid. They are commonly implemented using state machines [52].

Key concepts of RB-EMS include [53]:

1. Operation Principle: The controller monitors the net power (Generation – Demand) and the Battery State of Charge (SOC) to determine the operating mode of the components (e.g., charging/discharging battery, turning on a diesel generator, or exporting power).
2. Common Operating Modes:
   i. Surplus Power: Excess renewable energy charges the battery storage (BESS). If the battery is fully charged, the excess energy is curtailed or exported to the grid.
   ii. Deficit Power: Battery discharges to meet demand. If the battery falls below a minimum threshold SOC_{MIN}, the backup generator is activated.
3. Key Advantages: Low computational cost, rapid real-time response, and reliability, making them ideal for microcontrollers in remote areas.

5.1.2. State-of-Charge (SOC) Based Control

SOC-based strategies represent a specific subset of rule-based management focused on protecting the battery, which is often the most expensive component of a mini-grid [54].

Key concepts of SOC-based control include [55]:

1. Safe Operating Range: Rules strictly maintain the battery SOC within a set interval, commonly between 20% and 100%, to prevent overcharging or deep discharge.
2. Dynamic Thresholds:
   i. If $\boldsymbol{SOC < SOC_{MIN}}$: The system prioritizes battery charging from available renewable sources or diesel generators.
   ii. If $\boldsymbol{SOC > SOC_{MAX}}$: Battery discharging is encouraged, or charging is stopped.
3. Hybrid Storage Control: In hybrid systems (e.g., Battery + Supercapacitor), SOC-based control ensures the battery handles long-term storage while the supercapacitor manages transient peaks to improve battery longevity.

5.1.3. Heuristic Methods (Operating Strategies)

Heuristic methods are experience-based, intuitive rules aimed at finding a good enough solution quickly rather than the mathematically perfect one [56].

Key concepts of heuristic methods include [57]:

1. Load Following Strategy (LFS): Renewable sources and batteries serve the load first. Generators are turned on only when renewable power and battery storage are insufficient to meet the load.
2. Cycle Charging Strategy (CCS): Similar to LFS, but when a generator is needed, it operates at its rated capacity to supply the load and simultaneously charge the battery, turning off only when a specific, high SOC is reached.
3. Rule-Based Modular Approach: A modern heuristic approach that dynamically adjusts rules based on the components currently available in the system, enabling flexible handling of grid-connected or islanded modes.

5.1.4 Comparison of Conventional Strategies

Table 5.1 presents a summary of conventional energy management strategies.

Table 5.1: Summary of conventional energy management strategies [58]:

Strategy	Primary Focus	Best Use Case
Rule-Based (RB)	Simple Logic (If-Then)	Low-cost, real-time local controllers
SOC-Based	Battery Longevity	Systems with high battery capacity
Load Following	Minimize Fuel Use	High renewable penetration systems
Cycle Charging	Reliable Charging	Areas with limited renewable energy

These conventional methods, while robust, are often combined with AI algorithms (e.g., Genetic Algorithm, PSO) to optimize the specific thresholds used in the rules, reducing operation costs further [59].

VI. COMMUNICATION AND MONITORING TECHNOLOGIES

6.1 IoT & IoT-based Solutions

Mini-grid remote monitoring systems leverage SCADA (Supervisory Control and Data Acquisition) architecture combined with IoT platforms like ThingSpeak to provide real-time visibility, data logging, and control of renewable energy assets (solar, wind, battery). These systems, often using microcontrollers, replace expensive traditional SCADA with low-cost, open-source solutions to improve performance, reduce maintenance, and enable remote management [60].

Key Components of Mini-Grid Remote Monitoring include [61]:

1. Data Acquisition (IoT Sensors): Sensors measure PV panel voltage, current, battery SOC (State of Charge), temperature, and inverter output. Common sensors include CT sensors (non-invasive current) and PZEM-004T modules for power quality.
2. Communication & Processing (RTU): Microcontroller systems act as Smart Remote Terminal Units (RTUs), collecting sensor data

and transmitting it over Wi-Fi, GSM, or GPRS to the cloud.
3. Cloud Platform (ThingSpeak): Acts as the IoT server, receiving data every 15–30 seconds (configurable) to provide real-time visualization (graphs) and data analytics.
4. SCADA HMI (Human Machine Interface): ThingSpeak dashboards, Blynk, or Emoncms provide user-friendly web or mobile applications to monitor and control assets remotely.

6.1.1. Role of ThingSpeak in Mini-Grid SCADA

ThingSpeak is a frequently used platform in this context because it allows for [61]:

1. Real-time Analytics: It instantly visualizes data, allowing for immediate performance evaluation of solar power.
2. MATLAB Integration: Enables advanced analytics, machine learning, and automatic control of load based on generation (e.g., turning on/off loads based on battery state).
3. Alerting Systems: Configured to provide notifications for abnormal conditions like overvoltage or battery overheating.

Advantages of IoT-Based SCADA for Mini-Grids [62]:

1. Cost-Effectiveness: Utilizing ESP32/Arduino significantly lowers the cost compared to commercial, PLC-based SCADA systems.
2. Remote Management: Operators can monitor and control, for example, grid-connected inverters and battery storage remotely via a smartphone or web app.
3. Performance Evaluation & Forecasting: Continuous logging enables detailed analysis of load profiles and power generation, assisting in optimal system sizing and preventative maintenance.
4. Reliability: The use of smart monitoring ensures reliable, 24/7, continuous operation of decentralized power sources.

Typical System Architecture [62]:

1. Sensors (e.g., Voltage, Current, Temperature) ->
2. Microcontroller (ESP32/IoT Node) ->
3. Internet (Wi-Fi/GPRS/GSM) ->
4. ThingSpeak Cloud (Data Processing & Storage) ->
5. User Dashboard (HMI: PC/Phone) ->
6. Remote Control Actions (via API).

6.2 Smart Meters & Pay-As-You-Go (PAYG)

Smart metering is the foundational technology for modernizing electricity distribution, serving as the core component of Advanced Metering Infrastructure (AMI). Smart meters enable two-way communication between utilities and consumers, which is critical for Demand Side Management (DSM)—influencing when and how consumers use energy—and for improving revenue collection by reducing losses and automating billing [63].

6.2.1 Role of Smart Metering in Demand Side Management (DSM)

Smart meters shift electricity demand from peak to off-peak periods, flattening the load profile and reducing strain on the grid.

Key benefits of smart meters for balancing grid demand include [64]:

1. Time-of-Use (ToU) and Dynamic Pricing: Smart meters record consumption in granular intervals, allowing utilities to offer time-based tariffs. This encourages consumers to run high-energy appliances (washers, EVs) during off-peak hours when electricity is cheaper.
2. Real-time Load Monitoring: Utilities use real-time data to identify high-demand "hotspots" and manage grid health, preventing transformer overloads.
3. Demand Response Programs: Smart meters enable automated, remote reduction of load during emergencies or peak demand, where consumers are incentivized to temporarily lower their consumption.
4. Renewable Energy Integration: Smart meters facilitate two-way power flow, enabling "prosumers" (consumers who produce energy)

to sell excess rooftop solar energy back to the grid, balancing supply with consumption.

5. Consumer Empowerment: In-home displays and app-based energy controls provide consumers with real-time feedback on their energy usage, promoting behavioural changes to save money and energy.

VII. DISCUSSION AND CONCLUSION

EMS is critical for integrating intermittent renewable energy sources (RES), ensuring reliability in islanded or grid-connected modes, and optimizing operational costs. Recent literature highlights a shift towards intelligent, AI-driven, and decentralized control architectures to manage increasing complexity, demand-side management, and energy storage systems (ESS).

Key themes and findings of this review paper are as follows:

1. Purpose of EMS: Essential for managing renewable energy volatility, improving operational reliability, reducing downtime, and ensuring power balance between generation and load.
2. Optimization Techniques: Research shows a heavy reliance on artificial intelligence (AI), and metaheuristic optimization algorithms (like Particle Swarm Optimization - PSO) for scheduling energy flows.
3. Architecture Trends: There is a notable transition from centralized control—vulnerable to single-point failures—toward decentralized and distributed control architectures (e.g., ADMM, Agent-based) that enhance scalability and privacy.
4. Key Challenges: High capital expenditure (CAPEX) for implementation, limited technical expertise, and the complexity of managing variable loads and intermittent generation.

These are the major components and technologies of EMS:

1. Renewable & Storage Integration: The primary focus is on managing solar PV and hybrid renewable energy systems alongside battery energy storage systems (BESS).
2. Demand Side Management (DSM): EMS tools are increasingly used for load balancing and shifting to reduce peak demand.
3. Communication Technologies: IoT-based systems are becoming standard for monitoring and control in smart grids.

These are the future directions and research gaps in EMS:

1. AI and Machine Learning: Increased focus on data-driven, intelligent EMS to manage uncertainty.
2. Bio-inspired Strategies: Underrepresented in current research, these are emerging as potential alternatives to traditional optimization techniques.
3. Inter-microgrid Management: Coordinated management of multiple microgrids in a community setting is a growing area of research.
4. Grid Modernization: Strong emphasis on integrating IEC 61850 and IEEE 1547 standards to enhance reliability, cybersecurity, and interoperability.

For rural applications, especially in areas like sub-Saharan Africa, the literature indicates that EMS improves the financial sustainability of mini-grids by reducing reliance on costly diesel generators, lowering operational costs, and boosting reliability.

REFERENCES

[1] Energypedia (2026). “Mini Grids.” Retrieved on 25 March 2026 from https://energypedia.info/wiki/Mini_Grids.

[2] L. Burrell (2021). “What’s so important about mini-grids?” Retrieved on 25 March 2026 from https://www.unido.org/stories/whats-so-important-about-mini-grids.

[3] Jibril (2020). “What are the components of a mini-grid?” Retrieved on 25 March 2026 from https://havenhillsynergy.com/components-mini-grid/

[4] J. Peters, M. Sievert, M. A. Toman (2019). “Rural electrification through mini-grids: Challenges ahead.” Energy Policy (Elsevier), Vol. 132, September 2019, Pages 27-31.

[5] M. Kumwenda (2023). “How microgrids can facilitate energy access and electrify rural Africa.” Retrieved on 25 March 2026 from https://www.theigc.org/blogs/climate-priorities-developing-countries/how-microgrids-can-facilitate-energy-access-and

[6] S. A. Vincent, A. Tahiru, R. O. Lawal, C. E. Aralu, and A. Q. Okikiola (2024). “Hybrid renewable energy systems for rural electrification in developing countries: Assessing feasibility, efficiency, and socioeconomic impacts.” World Journal of Advanced Research and Reviews, 2024, 24(02), 2190–2204.

[7] P. C. Ohiri, E. Mfonobong, C. Ogomaka, and A. Chika (2025). “Impact of renewable energy integration on grid stability: A case study of Nigeria's power system.” World Journal of Advanced Engineering Technology and Sciences 14(03):199-204. DOI:10.30574/wjaets.2025.14.2.0058

[8] ECOGREENENERGY (2026): “EMS Explained: What Different Types of Energy Management Systems Actually Do.” Retrieved on 25 March 2026 from https://eco-greenenergy.com/ems-explained-what-different-types-of-energy-management-systems-actually-do/

[9] S. P. R. Kumar, S. Kalaimagal, and V. D. Earshia (2025). “Energy-Efficient Optimal Scheduling of Renewable Energy Sources in Power Systems Using Genetic Algorithms and Support Vector Machines.” International Journal of Computational Intelligence Systems, 18(1). DOI:10.1007/s44196-025-01045-6

[10] N. A. Kablar (2019). “Renewable Energy: Wind Turbines, Solar Cells, Small Hydroelectric Plants, Biomass, and Geothermal Sources of Energy.” Journal of Energy and Power Engineering 13 (2019) 162-172. doi: 10.17265/1934-8975/2019.04.004

[11] O. Erdinc and M. Uzunoglu (2012). “Optimum design of hybrid renewable energy systems: Overview of different approaches.” Renewable and Sustainable Energy Reviews, Vol. 16, Issue 3, 2012, pp. 1412-1425. https://doi.org/10.1016/j.rser.2011.11.011.

[12] A. A. Patil, R. Arora, R. Arora, and S. N. Sridhara (2024). “Techno-Economic Analysis of Solar, Wind, and Biomass Hybrid Renewable Energy Systems to Meet Electricity Demand of a Small Village in Bihar State of India.” Nature, Environment, and Pollution Technology, Vol. 23, No. 3, pp. 1261-1283, 2024. https://doi.org/10.46488/NEPT.2024.v23i03.003

[13] Seplos (2025). “A Comprehensive Guide to Lithium-Ion Battery Energy Storage Systems (BESS).” Retrieved on 26 March 2026 from https://www.seplos.com/a-comprehensive-guide-to-lithium-ion-battery-energy-storage-systems-bess.html

[14] Energy Market Authority (2020). “Handbook for Energy Storage Systems.” Retrieved on 26 March 2026 from https://www.ema.gov.sg/content/dam/corporate/resources/educational-materials/handbook/handbook-pdfs/english/EMA-Resources-Educational-Materials-Handbook-Energy-Storage-Systems-20201022.pdf

[15] BSLBATT (2025). “What Are the Different Types of Battery Energy Storage Systems?” Retrieved on 26 March 2026 from https://bslbatt.com/blogs/types-of-battery-energy-storage-systems-comparison-guide/

[16] M. B. Medha, I. Mahmud, M. Hasanuzzaman (2026). “Chapter 14 - Electrical energy storage technology,” In: M. Hasanuzzaman (Editor): Advanced Renewable Energy Conversion Technologies and Power Plant Engineering, ed. by Elsevier, 2026, pp. 503-549. ISBN 9780443288920, https://doi.org/10.1016/B978-0-443-28892-0.00023-2.

[17] K. R. Ngoy, V. K. Lukong, K. O. Yoro, J. B. Makambo, N. C. Chukwuati, C. Ibegbulam, O. Eterigho-Ikelegbe, K. Ukoba, and T. Jen, “Lithium-ion batteries and the future of sustainable energy: A comprehensive review.” Renewable and Sustainable Energy Reviews, Vol. 223, 2025, 115971, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2025.115971.

[18] E. Bryce (2024). “Flywheel Energy Storage: A Promising Alternative to Batteries for Balancing

Solar Power." Retrieved on 26 March 2026 from https://www.bryceenergyservices.com/2024/10/05/flywheel-energy-storage-a-promising-alternative-to-batteries/.

[19] D. A. Elalfy, E. Gouda, M. F. Kotb, V. Bureš, and B. E. Sedhom, "Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends." Energy Strategy Reviews, Vol. 54, 2024, 101482, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2024.101482.

[20] Opie, N. (2023). "AC vs DC-coupled BESS: the pros and cons," Retrieved on 26 March 2026 from https://ratedpower.com/blog/ac-vs-dc-coupled-bess/

[21] N. N. Opiyo, "A comparison of DC- versus AC-based mini-grids for cost-effective electrification of rural developing communities." Energy Reports, Vol. 5, 2019, pp. 398-408, ISSN 2352-4847. https://doi.org/10.1016/j.egyr.2019.04.001.

[22] B. Wu (2025). "Hybrid vs. Standard Inverters for Your Home Battery System?" Retrieved on 27 March 2026 from https://www.anernstore.com/blogs/off-grid-solar-solutions/hybrid-vs-standard-inverter-home-battery

[23] K. Zuo and L. Wu, "A review of decentralized and distributed control approaches for islanded microgrids: Novel designs, current trends, and emerging challenges." The Electricity Journal, Vol. 35, Issue 5, 2022, 107138, ISSN 1040-6190, https://doi.org/10.1016/j.tej.2022.107138.

[24] TUDelft (2018), "Centralized vs decentralized control," Retrieved on 27 March 2026 from https://delftxdownloads.tudelft.nl/PV4x/Week_5/PV4x_2018_Week_5_5-3_Centralized_and_decentralized_control-transcript.pdf

[25] A. Kumar and N. A. Prabha, "A comprehensive review of DC microgrid in market segments and control techniques." Heliyon, Vol. 8, Issue 11, 2022, e11694, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2022.e11694.

[26] Y. Sabri, N. El Kamoun, and F. Lakrami, "A Survey: Centralized, Decentralized, and Distributed Control Scheme in Smart Grid Systems." 7th Mediterranean Congress of Telecommunications (CMT), October 2019. DOI:10.1109/CMT.2019.8931370

[27] S. Ishaq, I. Khan, R. Syed, T. Hussain, A. Iqbal, and Elavarasan R. M., "A review on recent developments in control and optimization of micro grids." Energy Reports. 8 (2022), 4085-4103. https://doi.org/10.1016/j.egyr.2022.01.080.

[28] E. Boyko, F. Byk, P. Ilyushin, L. Myshkina, and K. Suslov, "Methods to improve reliability and operational flexibility by integrating hybrid community mini-grids into power systems." Energy Reports. Vol. 9, Supplement 9, 2023, Pages 481-494, ISSN 2352-4847. https://doi.org/10.1016/j.egyr.2023.06.038.

[29] Y. Wu, A. Wanume, and V. Modi, "Leveraging load shedding and daytime loads to improve mini-grid economics. Energy Policy." Volume 209, Part B, 2026, 115004, ISSN 0301-4215. https://doi.org/10.1016/j.enpol.2025.115004.

[30] S. Al-Agtash, "Literature Review of Microgrid Control Functions and Services." Energy Studies Review Vol 25 (1) 2025.

[31] T. Skrjanc, R. Mihalic, and U. Rudez, "A systematic literature review on under-frequency load shedding protection using clustering methods." Renewable and Sustainable Energy Reviews. Vol 180, 2023, 113294, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2023.113294.

[32] B. L. N. Phung and T. N. Le, "Load Shedding in Microgrids with Consideration of Voltage Quality Improvement." Engineering, Technology & Applied Science Research. Vol. 11, No. 1, 2021, 6680-6686.

[33] Balogun, A. Olajube, and A. Awelewa, S. Agoro, F. Okafor, T. Sanni, I.Samuel, and A. Ajilore, "Control strategies in enhanced stand-alone mini-grid operations for the NESI–an overview," Frontiers in Energy Research. 2024.1397482. https://doi.org/10.3389/fenrg.2024.1397482

[34] E. Mbinkar, A. Asoh, D. Tchuidjan, and A. Baldeh, "Design of a Photovoltaic Mini-Grid System for Rural Electrification in Sub-Saharan Africa," Energy and Power Engineering, 13, 91-110. doi: 10.4236/epe.2021.133007.

[35] M. Hosseina, M. S. Moghaddam, and A. Hassannia, "Optimizing energy and load

management in island microgrids for enhancing resilience against resource interruptions," Sci Rep 15, 16297 (2025). https://doi.org/10.1038/s41598-025-99974-x

[36] X. Yang, H. Zhou, and J. Gao, "Enhancing renewable energy productivity and energy efficiency of energy projects: How does cost of capital influence?" Energy Strategy Reviews, Vol. 57, 2025, 101608, ISSN 2211-467X, https://doi.org/10.1016/j.esr.2024.101608.

[37] S. Ross (2025). "CapEx vs. OpEx: Key Differences Explained." Retrieved on 27 March 2026 from https://www.investopedia.com/ask/answers/112814/whats-difference-between-capital-expenditures-capex-and-operational-expenditures-opex.asp

[38] N. X. Bản (2025). "What Is An EMS? And Its Role In Emission Reduction." Retrieved on 27 March 2026 from https://udata.ai/blog/what-is-an-ems-and-its-role-in-emission-reduction

[39] G. Ruzive, C.Y. van Staden, and K.S. Garner, "Maximising Renewable Energy Penetration in South Africa: Challenges, Problems and Solutions," In: Trois, C., Kaseke, R., Sempiira, J.E. (eds) Proceedings of the 2024 Southern African Sustainable Energy Conference. SASEC 2024. Springer Proceedings in Energy. Springer, Cham. https://doi.org/10.1007/978-3-032-12579-8_53

[40] V.B. Murali, V. S. Melkeri, S. Goel, and K. R. K. V. Prasad, "Two stage energy management for maximizing renewable energy penetration," Engineering Review, Vol. 45, No. 1.

[41] Aščerić, and M. Čepin, "Improving power distribution system reliability via optimized Microgrid integration and storage management," Reliability Engineering & System Safety, Vol. 264, Part B, 2025, 111386, ISSN 0951-8320. https://doi.org/10.1016/j.ress.2025.111386.

[42] L. D. Mangate, H. Alabdeli, R. Agarwal, and T. Saravanan, "Adaptive Energy Management System for Enhancing Efficiency and Reliability in Hybrid Renewable Energy Systems," E3S Web of Conferences 591, 01015 (2024). DOI:10.1051/e3sconf/202459101015

[43] B. Abu-Salih, P. Wongthongtham, G. Morrison, K. Coutinho, M. Al-Okaily, and A. Huneiti, "Short-term renewable energy consumption and generation forecasting: A case study of Western Australia," Heliyon, Vol. 8, Issue 3, 2022, e09152, ISSN 2405-8440.https://doi.org/10.1016/j.heliyon.2022.e09152.

[44] IBM (2025). What is load forecasting? Retrieved on 27 March 2026 from https://www.ibm.com/think/topics/load-forecasting

[45] Mystakidis, P. Koukaras, N. Tsalikidis, D. Ioannidis, and C. Tjortjis, "Energy Forecasting: A Comprehensive Review of Techniques and Technologies," Energies, 17(7), 1662. https://doi.org/10.3390/en17071662

[46] T. Mustafa and O. S. A. Al-Yozbaky, "Forecasting energy demand and generation using time series models: A comparative analysis of classical, grey, fuzzy, and intelligent approaches," Franklin Open, Vol. 12, 2025, 100350, ISSN 2773-1863, https://doi.org/10.1016/j.fraope.2025.10035

[47] Mystakidis, P. Koukaras, N. Tsalikidis, D. Ioannidis, and C. Tjortjis, ”Energy Forecasting: A Comprehensive Review of Techniques and Technologies," Energies, 17(7), 1662. https://doi.org/10.3390/en17071662.

[48] M. Hasan, Z. Mifta, S. J. Papiya, P. Roy, P. Dey, N. A. Salsabil, N. Chowdhury, and O. Farrok, "A state-of-the-art comparative review of load forecasting methods: Characteristics, perspectives, and applications," Energy Conversion and Management: X, Vol. 26, 2025, 100922, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2025.100922.

[49] S. A. Soliman and A. M. Al-Kandari, "3 - Load Modeling for Short-Term Forecasting," In: S. A. Soliman and Al-Kandari A. M. (Editors). Electrical Load Forecasting, Butterworth-Heinemann, 2010, Pages 79-97, ISBN 9780123815439. https://doi.org/10.1016/B978-0-12-381543-9.00003-8.

[50] K. Misiurek, T. Olkuski, and J. Zyśk, "Review of Methods and Models for Forecasting Electricity Consumption," Energies, 18(15), 4032 (2025). https://doi.org/10.3390/en18154032

[51] M.S. Bakare, A. Abdulkarim, A. N. Shuaibu, "Energy management controllers: strategies,

coordination, and applications," Energy Inform 7, 57 (2024). https://doi.org/10.1186/s42162-024-00357-9

[52] S. Jamal, J. Pasupuleti and J. Ekanayake, "A rule-based energy management system for hybrid renewable energy sources with battery bank optimized by genetic algorithm optimization," Sci Rep 14, 4865 (2024). https://doi.org/10.1038/s41598-024-54333-0

[53] M. A. Shehu, K. Talapiden, T. T. Chau, A. Haruna, M. Aly, V. Gali, T. D. Do, and A. B. Alhassan, "Control and energy management of standalone microgrids in remote areas: A review of recent advances, challenges, and opportunities for future research," Engineering Science and Technology, Vol. 75, 2026, 102288, ISSN 2215-0986. https://doi.org/10.1016/j.jestch.2026.102288.

[54] Behzadi and S. Sadrizadeh, "A rule-based energy management strategy for a low-temperature solar/wind-driven heating system optimized by the machine learning-assisted grey wolf approach," Energy Conversion and Management, Vol. 277, 2023, 116590, ISSN 0196-8904. https://doi.org/10.1016/j.enconman.2022.116590.

[55] N. A. I. Basit, N. Rosmin, A. H. Mustaamal, S. M. Hussin, and D. M. Said, "A Simple Energy Management System for a Micro Grid System Using Rule-Based Algorithm," In: Wahab, N.A., Mohamed, Z. (Editors), Control, Instrumentation and Mechatronics: Theory and Practice. Lecture Notes in Electrical Engineering, vol 921. Springer, Singapore. https://doi.org/10.1007/978-981-19-3923-5_24

[56] S. Nema, V. Prakash, & H. Pandžić, "The role of thermostatically controlled loads in power system frequency management: A comprehensive review," Sustainable Energy, Grids and Networks, Vol. 42, 2025, 101680, ISSN 2352-4677. https://doi.org/10.1016/j.segan.2025.101680

[57] Micangeli, D. Fioriti, P. Cherubini, and P. Duenas-Martinez, "Optimal Design of Isolated Mini-Grids with Deterministic Methods: Matching Predictive Operating Strategies with Low Computational Requirements," Energies, 13(16), 4214 (2020). https://doi.org/10.3390/en13164214

[58] S. Yun and J. Han, "Comparative Evaluation of Power Management Strategies in Multi-Stack Fuel Cell-Battery Hybrid Truck via TOPSIS," Batteries, 12(2), 65 (2026). https://doi.org/10.3390/batteries12020065

[59] S. Jamal, J. Pasupuleti, and J.Ekanayake, "A rule-based energy management system for hybrid renewable energy sources with battery bank optimized by genetic algorithm optimization," Sci Rep 14, 4865 (2024). https://doi.org/10.1038/s41598-024-54333-0

[60] M. O. Qays, M. M. Ahmed, M. A.Parvez-Mahmud, A. Abu-Siada, S. M. Muyeen, M. L. Hossain, F. Yasmin, and M. M. Rahman, "Monitoring of renewable energy systems by IoT-aided SCADA system," Energy Science & Engineering, 10(6), p. 1874-1885 (2022). https://doi.org/10.1002/ese3.1130

[61] G. M. Rafi, U. P. Reddy, P.Pratheep and D. P. Kumar, "IoT-based Industrial SCADA System for Real-Time Monitoring and Automated Alerts," 2025 8th International Conference on Computing Methodologies and Communication (ICCMC), Erode, India, 2025, pp. 299-304. doi: 10.1109/ICCMC65190.2025.11140742.

[62] M. Nkinyam, C. O.Ujah, C. O. Asadu, B. Anyaka, and P. A. Olubambi, "Development of a low-cost monitoring device for solar electric (PV) system using internet of things (IoT)," Results in Engineering, 28 (2025) 107324.

[63] K. Sharma, A. Malik, W. Abdelfattah, I. Batra, and M. Shabaz, "A smart electricity consumption management framework using Internet of Things (IoT) to optimize electricity demand, Measurement: Sensors," 33 (2024), 101218, ISSN 2665-9174, https://doi.org/10.1016/j.measen.2024.101218.

[64] PLCGroup (2026), "How Smart Energy Meters Are Powering A More Flexible Electricity Grid," Retrieved on 27 March 2026 from https://www.plcgroup.com/how-smart-energy-meters-are-powering-a-more-flexible-electricity-grid/