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A Layered Architecture for Renewable-Rich Microgrid Optimization Integrating Forecasting, Battery Scheduling, Demand Response, and Operator Override

Fatima El Idrissi^{1*}, Samira Bennani¹

Abstract

Renewable-rich microgrids face operational complexity from variable generation, storage dynamics, flexible loads, and the need for human oversight. A layered architecture can manage this complexity by separating functions while preserving coordination. Existing microgrid control architectures often entangle forecasting, scheduling, demand response, and supervisory control. This can make energy management systems brittle, difficult to maintain, and insufficiently accommodating of operator override. This article proposes a layered architecture that cleanly separates forecasting, battery scheduling, demand response, and operator override functions. The aim is to support modular design, resilient operation, and transparent human supervisory control. The architecture is developed conceptually using established ideas from microgrid energy management, hierarchical control, renewable integration, storage scheduling, demand response, and human-in-the-loop supervision. No experiments are conducted, and no quantitative results are presented. The architecture comprises four layers with defined functions, inputs, outputs, decision horizons, and interfaces. A validation plan is reserved for the second part of the article, while this part establishes the architecture logic and the forecasting layer. The proposed architecture offers a blueprint for building modular, resilient, and human-centred microgrid energy management systems. It is intended as a conceptual reference model for future implementation, testing, and refinement.

Keywords Demand response, Microgrid, Layered architecture, Forecasting, Battery scheduling, Operator override

*Correspondence:

Fatima El Idrissi
fatima.idrissi@gmail.com

¹ Department of Electrical Networks and Smart Energy, Faculty of Engineering, Mohammed V University, Rabat, Morocco

Introduction

Renewable-rich microgrids increasingly operate as cyber-physical energy systems in which distributed solar photovoltaic generation, wind generation, battery storage, controllable loads, and grid-interconnection constraints must be coordinated in real time. A layered automation architecture has been shown to be useful for heterogeneous monitoring and control environments because it separates measurement, communication, decision, and supervisory functions into more manageable modules [1]. In microgrid energy management, this separation is especially important because the same system must support local reliability, economic dispatch, renewable utilization, and safe interaction with operators. This article therefore frames microgrid optimization as an architectural design problem rather than as a single optimization formulation.

The operational challenge is intensified by uncertainty, because renewable generation and demand evolve across different time scales and with different levels of predictability. Forecast-informed energy management has been identified

as a core need for microgrid operation because weather, irradiance, wind, and load forecasts shape scheduling decisions before real-time control action occurs [2]. Probabilistic solar forecasting can further improve operational awareness by allowing the controller to reason about plausible deviations rather than a single deterministic trajectory [3]. A layered architecture is therefore designed to let uncertainty information pass from forecasting to scheduling without forcing every layer to solve the same prediction problem.

Battery energy storage adds another architectural requirement because it behaves simultaneously as a buffer, an economic resource, and a degrading physical asset. Community microgrid scheduling studies have treated battery cost and operational state as central components of energy management, showing that storage dispatch cannot be reduced to a simple charge-discharge rule [4]. Battery degradation modelling also affects microgrid energy management because dispatch decisions that appear economical in the short term may reduce long-term storage value [5]. The proposed architecture therefore treats battery scheduling as a dedicated layer that receives forecasts, coordinates with demand response, and exposes operational constraints to the operator.

Demand response and human supervision complete the architectural problem because microgrid optimization is not only a machine scheduling task. Incentive-based demand response has been used to reshape microgrid operation under renewable uncertainty, which indicates that flexible demand should be treated as an active controllable resource rather than as passive consumption [6]. At the same time, predictive energy management with pre-emptive load shedding shows that abnormal conditions may require supervisory choices that cannot be fully delegated to autonomous logic [7]. This article contributes a conceptual layered architecture in which automated forecasting, battery scheduling, and demand response are coordinated with an operator override layer that preserves human authority during emergencies and ambiguous operating states.

Architecture Requirements

Functional requirements

The architecture is designed to support four functional capabilities: forecasting, battery scheduling, demand response coordination, and operator override. Reviews of microgrid energy management systems emphasize that control, optimization, monitoring, communication, and scheduling functions must be organized coherently if the system is to remain maintainable as distributed energy resources expand [8]. The forecasting layer would estimate demand and renewable availability, while the battery scheduling layer would translate those estimates into feasible storage plans. The demand response layer would coordinate flexible loads, and the operator override layer would supervise, intervene, and authorize exceptional actions.

Real-time and near-real-time constraints

The architecture must distinguish between real-time control actions and near-real-time planning decisions because microgrid functions operate across different horizons. Model predictive control approaches for microgrids illustrate the value of rolling-horizon decision-making, where updated measurements and forecasts continually reshape operational plans [9]. The proposed design therefore assigns slower prediction and scheduling functions to planning-oriented layers while preserving fast adjustment pathways for dispatch, demand response, and emergency override. This separation is intended to reduce computational coupling while keeping the system responsive to renewable variability and load disturbances.

Human-operator interface needs

The operator interface must present actionable information rather than overwhelming the user with raw telemetry, optimization variables, or algorithmic detail. Reviews of building-integrated and building microgrid control show that practical systems need interpretable coordination between automated control and building or facility operators [10]. The

operator override layer would therefore expose forecast confidence, battery state, demand response commitments, alarms, and recommended actions in a supervisory interface. Its purpose is not to replace automated layers but to provide a structured pathway for human judgment when safety, resilience, comfort, or institutional priorities require intervention.

Existing Architecture Limits

Common control architectures

Microgrid control architectures are often described as hierarchical, distributed, centralized, or hybrid, with each structure offering a different balance between coordination and autonomy. Hierarchical predictive control has been proposed to manage microgrid energy decisions through organized control levels, showing the usefulness of decomposition across operational scales [11]. Broader reviews of hierarchical control for building microgrids similarly indicate that primary, secondary, and tertiary control layers can clarify electrical control responsibilities [12]. However, these control hierarchies do not always specify how forecasting, demand response, battery degradation management, and operator override should interact as an integrated energy management architecture.

Limitations in flexibility and human interaction

Existing energy management designs can become inflexible when forecasting, scheduling, and actuation are tightly embedded in one optimization block. Critical reviews of energy management strategies for microgrids note that uncertainty handling, control method selection, and operational scalability remain persistent challenges [13]. When human interaction is not represented as a formal layer, manual intervention may occur through ad hoc alarms, emergency switches, or informal operating procedures rather than through a traceable supervisory interface. The proposed architecture addresses this limitation by treating operator override as a designed control function with defined inputs, outputs, and reversion logic.

The gap this work addresses

The gap addressed here is not the absence of microgrid optimization algorithms but the absence of a clear conceptual architecture that coordinates automated optimization with human authority. Studies of multi-microgrid coordination with demand-side management demonstrate the value of hierarchical energy management, yet they primarily emphasize coordinated optimization rather than operator-centred override design [14]. Reviews of machine-learning-based and classical hierarchical control methods also show that many control frameworks focus on algorithmic performance, communication structures, or distributed autonomy rather than on explicit human-machine governance [15]. This article therefore proposes a four-layer architecture that makes forecasting, battery scheduling, demand response, and override responsibilities explicit and interoperable.

Proposed Layered Architecture

High-level architecture diagram (described)

The architecture can be represented conceptually as a vertical stack with information flowing upward from measurements and forecasts into operational decisions, while supervisory commands and constraints flow downward from the operator layer. At the base of the conceptual stack, field devices, meters, inverters, weather feeds, and building management systems provide data to the forecasting layer, which is consistent with the monitoring and automation logic used in multi-layered photovoltaic microgrid architectures [1]. The forecasting layer sends uncertainty-aware estimates to the battery scheduling and demand response layers, while these layers return feasibility constraints, expected flexibility, and operational risk indicators. The operator override layer sits above the automated layers, not as a permanent bottleneck, but as a supervisory authority that can approve, modify, suspend, or reverse automated actions.

Figure 1 illustrates the proposed human-supervised layered microgrid architecture, showing how field measurements and forecasts move upward into automated optimization layers while operator constraints, override commands, and reversion instructions flow downward to maintain resilient and accountable control.

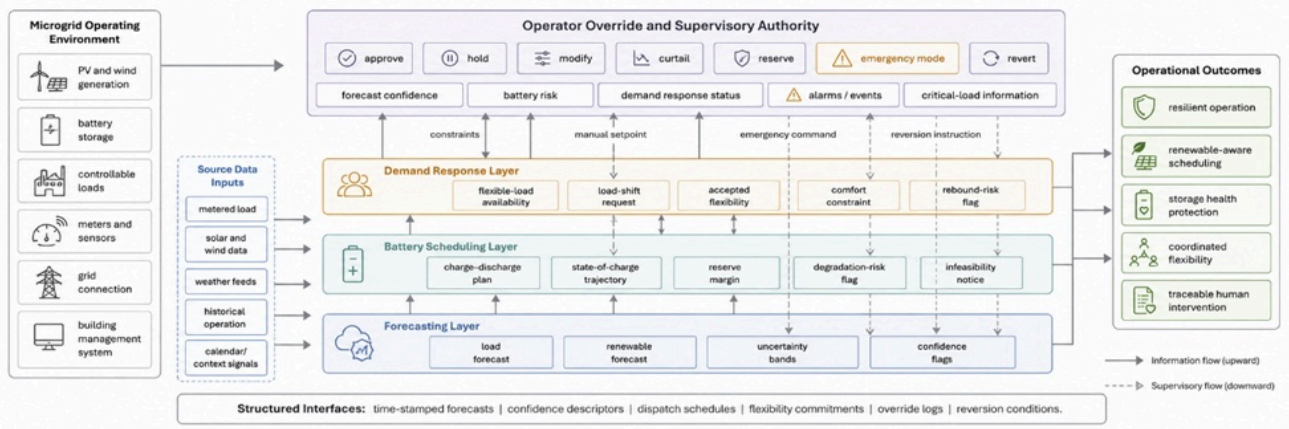


Figure 1. Layered Human-Supervised Architecture for Renewable-Rich Microgrid Optimization

Layer responsibilities overview

Each layer has a bounded decision scope so that the architecture can remain modular even as algorithms or assets change. Microgrid energy management reviews emphasize that different methods are suited to different functions, including forecasting, optimization, storage management, and control, which supports separating responsibilities rather than embedding all decisions in one monolithic controller [16]. The forecasting layer is responsible for prediction, the battery scheduling layer for storage dispatch planning, the demand response layer for flexible load coordination, and the operator override layer for supervisory intervention. This separation allows a forecasting model to be replaced, a battery degradation model to be refined, or a demand response tariff to be updated without redesigning the entire system.

Inter-layer communication and data flow

The architecture is designed around structured interfaces rather than informal data exchange. Forecasting studies using hybrid methods for short-term load prediction demonstrate that forecast outputs can be produced as operational inputs for subsequent energy management decisions rather than as standalone analytics [17]. In the proposed architecture, the forecasting layer would publish time-stamped load, solar, and wind estimates with confidence descriptors, while the battery scheduling layer would publish charge-discharge plans, state-of-charge trajectories, and constraint violations. The demand response layer would publish flexible load availability and accepted response actions, and the operator layer would publish override commands, priority rules, and reversion conditions.

Resilience and modularity benefits

The principal resilience benefit of the layered architecture is that faults, uncertainty, or degraded performance in one function need not disable the entire energy management system. Robust microgrid operation using ensemble weather forecasts shows that renewable uncertainty can be handled more effectively when forecast information is represented explicitly in operational planning [18]. Similarly, comprehensive reviews of individual and community microgrids indicate that modular control and optimization structures are important for adapting to different ownership models, device portfolios, and operating objectives [19]. **Table 1** summarizes the four-layer architecture by identifying each layer's primary function, key interface variables, and decision horizon.

Table 1. Overview of the Four-Layer Architecture

Layer	Primary function	Key inputs	Key outputs	Decision horizon	Interface with adjacent layers
Forecasting layer	Estimate short-term and near-term load, solar generation, wind generation, and uncertainty conditions	Metered demand, weather forecasts, irradiance data, wind data, historical operating data, calendar variables	Load forecasts, solar forecasts, wind forecasts, uncertainty bands, confidence flags	Minutes to day-ahead	Sends probabilistic forecasts to battery scheduling and demand response layers; receives data-quality alerts from field systems and override constraints from the operator layer
Battery scheduling layer	Plan and revise battery charge-discharge behavior while respecting state-of-charge, reserve, degradation, and market or tariff objectives	Forecasts, state of charge, battery limits, degradation parameters, electricity price signals, reserve requirements	Dispatch schedule, reserve margin, state-of-charge trajectory, degradation-risk flag, infeasibility notice	Intra-day to real time	Receives forecasts and flexibility signals; sends storage feasibility and risk information to demand response and operator layers
Demand response layer	Coordinate flexible demand through price-based, incentive-based, or direct-load-control mechanisms	Forecasted net load, battery schedule, flexible load availability, customer constraints, incentive rules, comfort limits	Demand response requests, accepted flexibility, load-shift plan, rebound-risk flag, participation status	Near-real-time to intra-day	Receives scheduling needs from battery layer; sends flexibility commitments and unresolved demand constraints to operator layer
Operator override layer	Provide supervisory control, emergency intervention, approval, suspension, and post-event reversion authority	Forecast confidence, battery status, demand response commitments, alarms, safety constraints, operator policy	Override command, manual setpoint, approval decision, emergency mode, reversion instruction	Immediate to event-based	Supervises all automated layers; can impose constraints, suspend automation, authorize emergency response, or return operation to automated control

Forecasting Layer

Load and renewable generation forecasting

The forecasting layer is designed to provide a shared predictive foundation for all downstream optimization decisions. Short-term photovoltaic forecasting using hybrid wavelet, particle swarm, and support vector machine approaches demonstrates that renewable prediction can combine meteorological and operational data to support microgrid scheduling [20]. For a renewable-rich microgrid, the layer would produce load, solar photovoltaic, and wind forecasts at horizons aligned with battery scheduling and demand response decisions. Its function is not to choose dispatch actions but to transform heterogeneous data into credible operational expectations.

Probabilistic outputs and uncertainty quantification

The forecasting layer should provide probabilistic outputs because deterministic point forecasts can hide uncertainty that is operationally important for storage reserves and flexible demand activation. Research on probabilistic solar forecasts for microgrid operation shows that uncertainty-aware prediction can support more efficient operating decisions under renewable variability [3]. Deep-learning-based probabilistic forecasting for community microgrids further indicates that renewable uncertainty can be represented in ways that are usable by higher-level energy management functions [21]. In the proposed architecture, forecast intervals, confidence flags, and scenario descriptors would be passed forward so that scheduling and override decisions can distinguish normal forecast error from abnormal uncertainty.

Interface to scheduling layer

The interface from the forecasting layer to the scheduling layer is designed as a formal contract that specifies data timing, forecast horizon, uncertainty format, and quality status. Robust multi-objective scheduling studies using machine-learning-based probabilistic forecasting show that scheduling models can use forecast scenarios as structured inputs rather than relying on fixed deterministic assumptions [22]. The forecasting layer would therefore provide synchronized demand, solar, and wind trajectories, along with uncertainty descriptors and data-quality warnings, to the battery scheduling layer. If forecast confidence falls below an acceptable threshold, the interface would also notify the operator override layer so that conservative scheduling, manual review, or emergency reserve policies could be activated.

Battery Scheduling Layer

Day-ahead and intra-day scheduling

The battery scheduling layer is designed to translate forecast information into feasible storage plans that can support renewable smoothing, peak management, reserve provision, and grid-interaction objectives. Unit commitment and economic dispatch formulations for microgrids show that storage scheduling must be coordinated with generation availability, load balance, and operational constraints rather than treated as an isolated charging rule [23]. The layer would operate on both day-ahead and intra-day horizons, using updated forecasts from the forecasting layer to revise charge-discharge plans as conditions change. Its outputs would include a dispatch schedule, a state-of-charge trajectory, reserve margins, and infeasibility notifications for the demand response and operator override layers.

Degradation-aware dispatch

The battery scheduling layer must also account for battery degradation because repeated cycling, high depth of discharge, and aggressive real-time corrections can reduce long-term asset value. Degradation-aware microgrid energy management studies show that the choice of degradation model can materially shape dispatch behaviour and operational priorities [5]. The architecture is therefore designed so that battery health indicators, cycling limits, and degradation-risk flags are embedded in the scheduling interface. This allows the operator layer to see when an economically attractive dispatch plan may conflict with long-term storage preservation.

Real-time adjustments

Real-time battery adjustment is designed as a constrained correction process rather than a complete replacement of the scheduling layer's plan. Community energy storage research under uncertain real-time prices shows that storage decisions may need to adapt to changing market or tariff conditions while still preserving system feasibility [24]. Stochastic microgrid scheduling work also indicates that reserves and uncertainty must be represented when storage is expected to support both economic and reliability objectives [25]. In the proposed architecture, real-time adjustments would be passed to the demand response layer when additional flexibility is needed and to the operator override layer when automated correction becomes insufficient or unsafe.

Demand Response Layer

Load flexibility characterization

The demand response layer is designed to characterize flexible demand as an operational resource with limits, preferences, rebound effects, and participation constraints. Optimization of renewable microgrids with demand-side management under uncertainty shows that controllable demand can support system balance when renewable output and load are uncertain [26]. The layer would classify loads according to interruptibility, shiftability, comfort sensitivity, response speed, and contractual availability. Its output would not simply be a load reduction command but a structured flexibility map that can be used by battery scheduling and operator supervision.

Incentive and price-based coordination

The demand response layer could coordinate flexible loads through price-based signals, incentive-based requests, or direct control, depending on the microgrid's market arrangement and customer agreements. IoT-based demand-side management and control schemes show that distributed sensing and communication can support automated load coordination in smart microgrids [27]. Community home energy management studies with batteries and electric vehicles further illustrate that demand response may need to coordinate household flexibility, storage, and mobility-related loads within the same operational framework [28]. In the proposed architecture, the layer would issue response requests, confirm accepted flexibility, and report unresolved demand constraints to the scheduling and operator layers.

Integration with battery and operator layers

The demand response layer is designed to coordinate with the battery scheduling layer so that flexible demand and storage are not dispatched against each other. Reviews of microgrid control methods emphasize that sustainable energy management requires coordinated control across generation, storage, and load-side resources [29]. When battery reserves are scarce, demand response could reduce stress on storage; when customer flexibility is limited, the battery layer could compensate within its health and reserve constraints. The operator override layer would receive the resulting flexibility commitments, comfort risks, and participation status so that manual intervention can account for both technical feasibility and user impact.

Operator Override Layer

Trigger conditions for override

The operator override layer is designed to activate when automated decisions require human review, emergency intervention, or policy-based judgment. Predictive energy management using pre-emptive load shedding shows that islanded photovoltaic microgrids may face conditions where automated actions intersect with service continuity and safety priorities [7]. Override triggers could include forecast-confidence collapse, battery infeasibility, excessive degradation risk, demand response non-participation, islanding events, protection alarms, communication failure, or operator-declared emergency states. The layer would therefore function as a supervisory authority that can constrain, suspend, modify, or reverse automated actions.

Override decision support tools

The operator interface should provide decision support that explains system state, predicted consequences, and available intervention modes. Reviews of power management in isolated direct-current microgrids show that operators and controllers must reason about stability, energy balance, storage limits, and load prioritization under constrained conditions [30]. The proposed interface would display forecast uncertainty, battery state of charge, degradation-risk indicators, demand response commitments, critical-load status, and recommended override options. The operator would interact

through structured controls such as approve, hold, curtail, shed, island, reconnect, reserve, or revert, rather than through unstructured manual setpoint changes alone.

Post-override reversion and learning

After an override, the architecture should support controlled reversion to automated operation rather than abruptly restoring all algorithmic decisions. Reviews of multi-microgrid energy management under uncertainty show that coordination becomes more difficult when local decisions, external uncertainty, and system-level constraints must be reconciled after disturbances [31]. The operator override layer would therefore issue reversion conditions, record the reason for intervention, and notify the forecasting, battery scheduling, and demand response layers that their operating assumptions have changed. Table 2 maps representative intervention scenarios to override modes, triggers, and required information from adjacent layers.

Table 2. Operator Override Scenarios and Intervention Modes

Operator intervention scenario	Override mode	Typical trigger	Required information from other layers	Intended reversion logic
Forecast confidence deteriorates during rapidly changing weather	Conservative scheduling override	Forecast layer reports low confidence or conflicting renewable scenarios	Forecast uncertainty bands, data-quality status, expected solar and wind deviation	Return to automated scheduling after forecast confidence stabilizes and updated scenarios are accepted
Battery state of charge approaches emergency reserve threshold	Reserve protection override	Battery layer reports reserve violation risk or infeasible dispatch	State-of-charge trajectory, degradation-risk flag, dispatch infeasibility notice	Restore automated dispatch only after minimum reserve margin is re-established
Demand response participation is lower than expected	Flexibility shortfall override	Demand response layer reports insufficient accepted load flexibility	Accepted flexibility, rejected requests, critical-load constraints, rebound-risk flag	Resume automated coordination after revised flexibility commitments are confirmed
Islanded operation begins unexpectedly	Emergency islanding override	Protection, grid-status, or communication alarm indicates islanding	Forecasted net load, battery reserve, flexible-load availability, critical-load priority	Reconnect or return to normal mode after grid status, synchronization, and reserves are verified
Operator identifies safety, comfort, or institutional priority conflict	Policy override	Human operator judges that automated action conflicts with local operating policy	Recommended automated action, affected loads, expected consequences, alternative actions	Resume automation after the operator records the reason and selects a bounded reversion condition

Validation Plan

Simulation and emulation environments

The validation plan is designed to test the architecture without claiming experimental results in this article. Reviews of recent microgrid energy management strategies show that simulation environments are useful for comparing control logic,

uncertainty handling, storage coordination, and demand response integration before deployment [32]. In the proposed plan, simulation would be used to emulate renewable variability, load uncertainty, battery constraints, demand response participation, and operator-triggered disturbances. The objective would be to verify interface behaviour, decision traceability, and safe coordination among layers rather than to report numerical superiority.

Hardware-in-the-loop testing

Hardware-in-the-loop testing could then examine whether the architecture's interfaces remain reliable when controllers, communication delays, inverters, storage emulators, and load controllers interact under realistic timing constraints. Methodological work on smart microgrid energy management with dispatchable renewable generation and distributed storage indicates that practical validation should consider how storage, renewable sources, and dispatch logic operate together in implementable environments [33]. The hardware-in-the-loop stage would test command timing, override latency, data-quality flags, fallback modes, and reversion from manual to automated operation. This stage would still be architectural and procedural, focusing on whether the layered design behaves coherently under stress.

Field pilot roadmap

A field pilot could assess whether the architecture is understandable, maintainable, and operationally useful for microgrid operators, facility managers, and participating customers. Microgrid forecasting and uncertainty management literature emphasizes that field operation must account for imperfect forecasts, changing operating conditions, and the practical limits of automated decision-making [34]. The pilot roadmap would begin with passive monitoring, proceed to advisory-mode recommendations, then limited automated scheduling, and finally supervised override-enabled operation. **Table 3** summarizes the validation stages, environments, metrics, and success criteria that could be used to evaluate the architecture without presenting actual results.

Table 3. Validation Plan Overview

Validation stage	Test environment	Architecture functions examined	Example metrics	Conceptual success criteria
Offline simulation	Software model of renewable-rich microgrid with synthetic or historical operating profiles	Forecast publication, battery scheduling logic, demand response coordination, override event handling	Interface completeness, infeasibility detection, forecast-quality flag propagation, action traceability	Each layer exchanges required information correctly and responds to abnormal conditions through defined interfaces
Co-simulation and emulation	Coupled power-system, communication, and control emulation environment	Timing consistency, data exchange, scenario handling, coordination between automated layers	Message latency, missing-data handling, scheduling update consistency, demand response acknowledgement	Automated layers remain coordinated despite delays, missing data, or changing renewable conditions
Hardware-in-the-loop	Controller hardware, inverter or storage emulator, load controller, and supervisory interface	Real-time command execution, override latency, fallback operation, reversion procedure	Command execution delay, override acknowledgement, safe fallback activation, operator confirmation time	Operator commands are executed predictably and automated control resumes only under defined reversion conditions

Advisory field pilot	Real microgrid operated with recommendations but limited automated actuation	Operator interpretability, forecast usefulness, scheduling transparency, demand response readiness	Operator acceptance, alarm clarity, recommendation traceability, rejected-action documentation	Operators understand recommendations and can evaluate override choices before automation is expanded
Supervised operational pilot	Field microgrid with bounded automated control and active override authority	Full layered coordination under normal and abnormal conditions	Override frequency, reversion completeness, communication availability, event log quality	The architecture supports safe, transparent, and recoverable coordination among forecasting, storage, demand response, and human supervision

Conclusion

This article proposed a layered architecture for renewable-rich microgrid optimization that separates forecasting, battery scheduling, demand response, and operator override into distinct but interacting layers. The design is conceptual and architecture-driven, with emphasis on responsibilities, interfaces, decision horizons, and operational logic rather than experimental performance.

The central value of the architecture is modularity. By assigning prediction, storage scheduling, flexible-load coordination, and supervisory intervention to separate layers, the design allows each function to evolve without destabilizing the entire energy management system.

The operator override layer is essential because renewable-rich microgrids may face conditions where automated optimization alone is insufficient. Human supervision provides a pathway for emergency action, policy judgment, safety prioritization, and controlled reversion after abnormal events.

Future implementation should focus on developing interoperable software interfaces, operator decision-support displays, and staged validation through simulation, hardware-in-the-loop testing, and field pilots. The architecture is intended to serve as a practical conceptual blueprint for resilient, explainable, and human-centred microgrid energy management.

Acknowledgements

None

Conflict of interest

None

Financial support

None

Ethics statement

None

Received: 29 Mar 2024

Revised: 11 May 2024

Accepted: 23 Jun 2024

Published online: 20 September 2024

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