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A Conceptual Framework for Digital-Twin-Assisted Microgrid Control: Resilience-Oriented Islanding, Renewable Forecast Uncertainty, and Battery Dispatch Recovery

Nokuthula Dlamini^{1*}, Siphso Zulu¹

Abstract

Microgrids are increasingly relied upon to maintain supply during disruptions, but their resilience depends on timely islanding, accurate renewable forecasts, and efficient battery dispatch. Digital twins offer a platform to integrate these functions into a coordinated control environment. Existing microgrid control architectures often treat islanding, forecast uncertainty, and battery recovery as separate problems. An integrated conceptual framework that unifies them within a digital-twin environment is therefore needed. This article proposes a conceptual framework for digital-twin-assisted microgrid control that coordinates resilience-oriented islanding, renewable forecast error handling, and battery dispatch recovery. The framework is intended as a design-oriented contribution rather than an experimental validation. The framework is developed through conceptual synthesis of digital twin architectures, microgrid resilience theory, forecasting uncertainty modeling, and battery storage control. No experiments, simulations, field measurements, or empirical results are reported. The framework describes a multi-layered control architecture that continuously assesses resilience, triggers islanding under forecast uncertainty, and manages battery dispatch for post-islanding recovery. Four tables summarize digital twin functions, forecast error types, control architecture, and resilience indicators. The framework provides a design blueprint for resilient microgrid controllers that leverage digital twins. It can guide future simulation studies, hardware-in-the-loop testing, and field validations.

Keywords Conceptual framework, Digital twin, Microgrid resilience, Islanding, Renewable forecast uncertainty, Battery dispatch recovery

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Introduction

Microgrids are increasingly conceptualized as resilience resources because they can sustain local supply when the main grid is degraded, unavailable, or unsafe to remain connected to [1]. However, this resilience function requires more than distributed generation; it requires coordinated sensing, forecasting, islanding, protection, dispatch, and recovery logic. Microgrid resilience can therefore be understood as a cyber-physical control problem in which electrical, informational, and operational layers must remain aligned during disturbance evolution. This article develops a conceptual framework in which a digital twin could be designed to support that alignment before, during, and after islanding.

Resilience-oriented microgrid control has been framed as a process of anticipating threats, absorbing disturbances, adapting operating modes, and recovering critical loads after disruption [2]. Digital twins extend this process by providing a synchronized virtual representation of the microgrid, allowing the controller to compare observed conditions with simulated contingencies and operational alternatives [3]. In such a setting, the twin would not merely visualize the microgrid but would support decision-making through state mirroring, model updating, and what-if analysis. This article positions the digital twin as the organizing layer through which islanding, renewable uncertainty, and battery recovery can be jointly interpreted.

Intentional islanding is central to this framework because the decision to separate from the main grid can either preserve or degrade resilience depending on timing, adequacy, and transition quality. Resilience-oriented islanding has been described as a strategy for reconfigurable distribution systems in which controlled separation can preserve service under severe disturbances [4]. Seamless microgrid transition further requires protection and control schemes that maintain voltage, frequency, and load balance during the change of operating mode [5]. A digital twin-assisted islanding logic could therefore evaluate both the immediate grid threat and the expected ability of local resources to sustain the islanded microgrid.

Renewable forecast uncertainty is also critical because islanding adequacy depends on future photovoltaic, wind, and load conditions rather than only on instantaneous measurements. Forecasting reviews show that renewable power predictions contain uncertainty arising from weather variability, model limits, and temporal aggregation [6]. Probabilistic photovoltaic and demand forecasting approaches indicate that uncertainty should be represented as distributions or scenarios rather than single deterministic trajectories [7]. The proposed framework therefore treats forecast error as an explicit input to islanding and battery dispatch decisions.

Battery energy storage provides the main recovery actuator in the framework because it can buffer renewable variability, support transition stability, and prioritize critical loads. Optimal microgrid scheduling studies show that battery storage must be coordinated with renewable and load uncertainty to avoid fragile islanded operation [8]. Storage-based resilience studies also suggest that batteries can increase the ability of buildings and microgrids to maintain service during grid outages [9]. The contribution of this article is to synthesize these ideas into a conceptual architecture that links digital twin monitoring, resilience-oriented islanding, renewable forecast error modeling, and battery dispatch recovery.

Conceptual Background of Microgrid Resilience

Defining microgrid resilience

Microgrid resilience can be defined as the ability of a local energy system to prepare for, absorb, adapt to, and recover from disruptive events while preserving critical functions. Reviews of microgrids as resilience resources emphasize that resilience differs from conventional reliability because it focuses on high-impact disturbances and degraded operating states rather than only routine interruption frequency [1]. In this article, resilience is conceptualized as a dynamic control property rather than a static asset attribute. A resilient microgrid would therefore require continuous situational awareness, mode-switching capability, and coordinated recovery logic.

Resilience threats and extreme events

Resilience threats include extreme weather, upstream grid faults, communication failures, renewable intermittency, equipment outages, and cyber-physical disruptions. A holistic microgrid resilience approach requires identifying threats, mapping vulnerabilities, and designing mitigation strategies that match the operational role of the microgrid [2]. Digital twin-assisted control could support this process by maintaining a structured representation of the microgrid's exposure, asset condition, load priority, and available flexibility. Such a representation would enable the controller to distinguish between normal variability and emerging threats that justify islanding preparation.

The resilience trapezoid and control phases

The resilience trapezoid can be used conceptually to describe performance degradation, degraded operation, restoration, and post-event recovery. Statistical studies of islanded microgrid resilience show that islanding performance is not only a binary question of survival but also a time-dependent trajectory of service preservation and recovery [10]. Within the proposed framework, the digital twin would map these phases onto control actions: pre-disturbance monitoring, disturbance detection, islanding execution, battery-supported stabilization, and staged restoration. This interpretation allows resilience to be treated as a sequence of decisions rather than a single post-event metric.

Role of storage and renewables in resilience

Renewables and storage jointly shape microgrid resilience because renewable generation can extend islanded operation while batteries can compensate for variability and support critical loads. Studies of photovoltaic, battery, and generator-based microgrids show that resilience and economics depend strongly on how resources are combined and dispatched during outages [11]. However, renewable generation also introduces uncertainty that can make islanding decisions risky when forecasts are inaccurate. The framework therefore conceptualizes storage not only as an energy buffer but also as a resilience recovery mechanism coordinated with forecast-error awareness.

Role of Digital Twins in Microgrid Control

Digital twin fundamentals for power systems

A digital twin for microgrid control can be conceptualized as a continuously updated virtual counterpart of physical assets, electrical states, control settings, and operating constraints. Microgrid digital twin research describes applications in monitoring, optimization, diagnostics, synchronization, and future operational planning [3]. In the proposed framework, the digital twin would function as the central interpretive layer between raw measurements and resilience actions. It would integrate physical models, data-driven forecasts, control rules, and operator-facing decision support.

State mirroring and synchronization

State mirroring and synchronization are essential because the twin must represent the actual microgrid with sufficient fidelity to support islanding and dispatch decisions. Digital twin scheduling studies show that a virtual microgrid environment can be used to reproduce operating conditions and test scheduling alternatives before implementation [12]. For resilience-oriented control, synchronization would include power flows, voltage profiles, frequency trends, state of charge, breaker status, renewable output, load priority, and communication health. The framework assumes that the twin should continuously reconcile measured data with model-estimated states to reduce decision errors during fast disturbances.

What-if analysis and contingency simulation

What-if analysis allows the digital twin to compare alternative futures under grid faults, renewable forecast errors, load changes, and battery dispatch strategies. Framework-oriented digital twin microgrid studies emphasize that twin environments can support application perspectives beyond monitoring, including operational assessment and scenario-based decision support [13]. In this article, what-if analysis is conceptualized as a resilience screening function that evaluates whether remaining grid-connected, preparing to island, or immediately islanding would better preserve critical loads. This function would be especially valuable when the disturbance is evolving and deterministic forecasts are insufficient.

Digital twin as a resilience decision support tool

The digital twin can be designed as a resilience decision support tool that converts synchronized state information and forecast uncertainty into recommended control actions. Digital twin-enhanced maintenance and risk-importance concepts suggest that virtual representations can prioritize components and actions according to their contribution to system risk [14].

Figure 1 illustrates the proposed digital-twin-assisted control architecture through which synchronized microgrid states, forecast uncertainty, resilience assessment, islanding coordination, battery recovery, and operator supervision are integrated into a single resilience-oriented decision pathway.

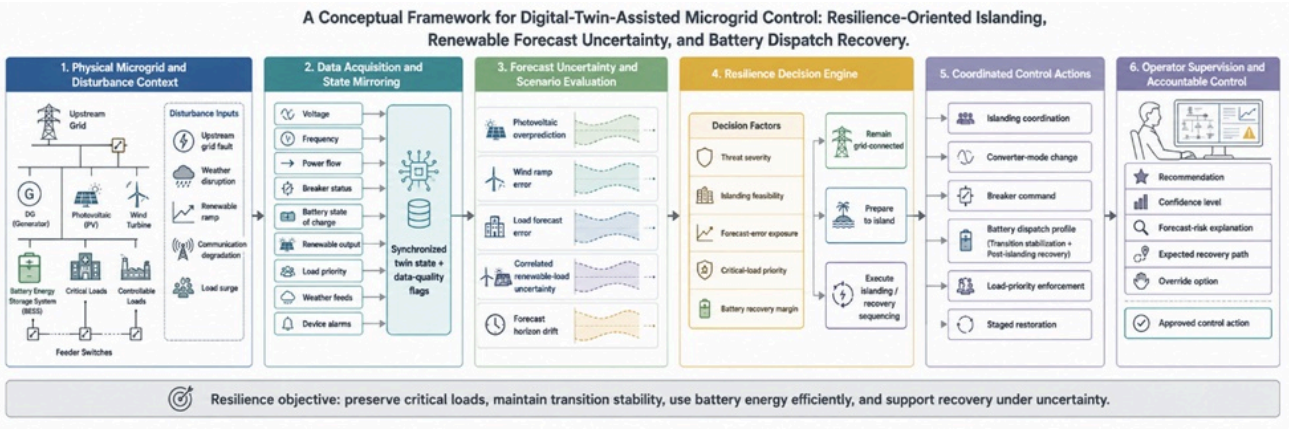


Figure 1. Digital-Twin-Assisted Resilience Control Architecture for Microgrid Islanding and Recovery

Table 1 summarizes how the proposed framework maps digital twin components to resilience-control functions. In this conceptual architecture, the twin would support operators and autonomous controllers by presenting islanding adequacy, battery recovery margin, forecast-error exposure, and expected service preservation.

Table 1. Digital Twin Components and Functions for Microgrid Resilience Control

Digital twin component	Conceptual function in microgrid control	Resilience relevance	Information flow
Physical asset mirror	Represents distributed generators, batteries, feeders, switches, converters, and controllable loads	Identifies which assets remain available for islanded operation	Field measurements and asset models flow into the twin state estimator
Electrical state estimator	Reconstructs voltage, frequency, power flow, loading, and state-of-charge conditions	Detects degradation before critical thresholds are crossed	Sensor streams are reconciled with network models and controller constraints
Forecast uncertainty module	Converts renewable and load forecasts into uncertainty bands or scenarios	Estimates adequacy risk before and after islanding	Weather, generation, and demand forecasts flow into scenario evaluation
Contingency simulator	Tests grid fault, feeder outage, renewable drop, and battery dispatch cases	Supports proactive islanding and recovery planning	Candidate events flow into what-if simulations and ranked control options
Resilience decision engine	Compares operating modes using threat, adequacy, and recovery indicators	Selects whether to remain grid-connected,	State, forecast, and contingency outputs flow into mode-selection logic

		prepare islanding, or island	
Battery recovery coordinator	Allocates battery power and reserve for transition support and load restoration	Preserves critical load and stabilizes islanded operation	State-of-charge and load-priority data flow into dispatch commands
Operator interface	Presents recommendations, alerts, confidence levels, and override options	Maintains human supervision during uncertain or high-risk actions	Decision recommendations flow to the operator and approved actions return to control layers

Resilience-Oriented Islanding Concept

Intentional islanding and resilience

Intentional islanding can be conceptualized as a resilience action that separates the microgrid from a threatening upstream condition before local service collapses. Resilience-oriented islanding research describes controlled separation as a way to preserve load supply when distribution-system reconfiguration alone is insufficient [4]. In the proposed framework, islanding would not be triggered only by fault detection but by a broader assessment of threat severity, forecasted adequacy, and recovery feasibility. This makes islanding a risk-informed decision rather than a purely protective response.

Criteria for islanding decisions

Islanding criteria should integrate electrical stability, local generation adequacy, battery state of charge, renewable forecast risk, critical load priority, and reconnection feasibility. Frequency-stability-constrained scheduling for seamless islanding shows that pre-islanding decisions must consider whether the microgrid can withstand the transition without unacceptable frequency excursions [15]. A digital twin-assisted decision engine could evaluate these criteria through near-real-time scenarios that compare the consequences of immediate, delayed, and avoided islanding. The islanding decision would therefore be expected to depend on both present states and near-future uncertainty.

Islanding transition and seamless operation

The islanding transition requires coordinated protection, converter control, synchronization logic, and dispatch adjustment so that the microgrid remains electrically stable after separation. Microgrid protection and control schemes for seamless transition emphasize the need for coordinated islanding and later grid synchronization [5]. In this framework, the digital twin could provide transition readiness checks before breaker operation, including voltage and frequency margins, battery response capability, and critical load balance. After islanding, the same twin would track whether operating conditions remain within acceptable resilience envelopes.

Digital twin-assisted islanding logic

Digital twin-assisted islanding logic can be conceptualized as a decision sequence that begins with disturbance detection, proceeds through adequacy assessment, and ends with controlled separation or continued grid-connected operation. Probabilistic distributed digital twin approaches for smart-grid stability and islanding indicate that twin-based methods can incorporate uncertainty into islanding-related stability assessment [16]. The proposed logic would evaluate whether forecasted renewable deficits, battery constraints, and grid disturbance severity threaten the resilience trajectory. If the expected performance loss exceeds a predefined resilience threshold, the controller could initiate islanding and activate battery recovery routines.

Renewable Forecast Error Modeling

Sources of forecast uncertainty in microgrids

Renewable forecast uncertainty arises from weather prediction error, spatial variability, model limitations, measurement noise, and sudden cloud or wind changes. Reviews of forecasting applications in renewable power systems highlight that prediction accuracy depends on data quality, forecasting horizon, resource type, and algorithm selection [6]. In microgrids, these errors are especially consequential because local balancing resources are limited compared with bulk power systems. The proposed framework therefore treats forecast uncertainty as a resilience input rather than as an external forecasting problem.

Probabilistic and scenario-based approaches

Probabilistic and scenario-based approaches can represent uncertainty by estimating ranges, distributions, quantiles, or multiple plausible renewable trajectories. Reviews of probabilistic photovoltaic and consumption forecasting show that uncertainty-aware forecasts can better support operational decisions than single-point predictions [7]. Robust optimization for hybrid microgrid operation has also shown that ensemble weather forecasts can inform decisions under uncertain renewable availability [17]. Within the proposed digital twin, forecast scenarios would be used to stress-test islanding adequacy and battery recovery plans before control actions are executed.

Impact of forecast errors on islanding adequacy

Forecast errors affect islanding adequacy because the microgrid may appear capable of islanded operation under expected generation but become insufficient under renewable shortfall. Studies of battery technologies under forecast uncertainty show that forecast errors can alter the value and role of storage in grid-connected microgrids [18]. If renewable output is overestimated, the controller may island with inadequate reserve; if renewable output is underestimated, it may delay islanding and expose critical loads to upstream failure. The framework therefore requires forecast-error-aware adequacy margins that link renewable uncertainty to battery reserve and load-restoration priorities.

Figure 2 shows how renewable and load forecast errors are transformed into scenario-based adequacy assessments that determine whether the microgrid should remain grid-connected, prepare for islanding, or execute controlled separation with battery reserve protection.

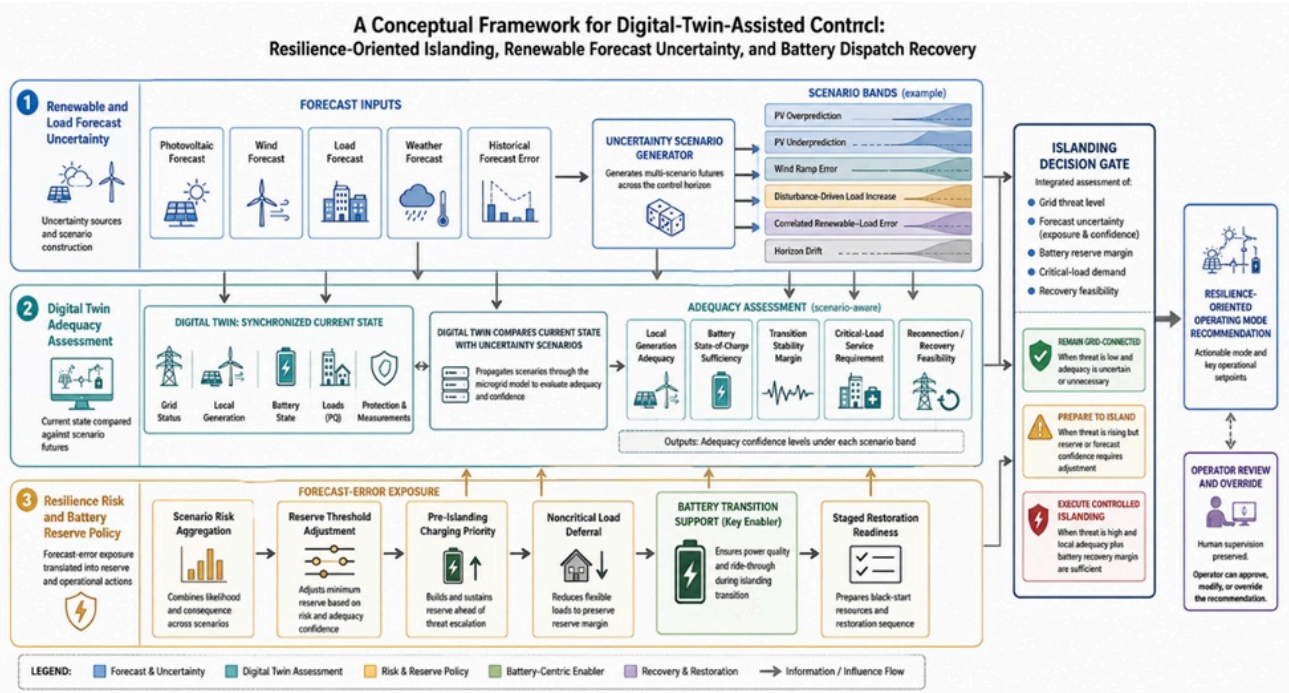


Figure 2. Forecast-Uncertainty-to-Islanding Decision Logic in Digital-Twin-Assisted Microgrid Control

Integrating forecast error into digital twin framework

Forecast error should be integrated into the digital twin through a module that receives renewable forecasts, estimates uncertainty, generates scenarios, and communicates adequacy risk to the islanding and battery dispatch layers. Optimal renewable-based microgrid scheduling under uncertainty demonstrates that photovoltaic and battery decisions should be jointly coordinated when renewable output is uncertain [19]. Table 2 classifies the main forecast error types that the proposed framework would use to inform islanding and recovery decisions. This integration would allow the twin to continuously update the confidence of islanding readiness as weather, load, and battery conditions change.

Table 2 highlights how different renewable forecast errors and their sources influence islanding decisions and battery dispatch strategies in digital twin–based microgrid management.

Table 2. Renewable Forecast Error Types, Sources, and Islanding Implications

Forecast error type	Main source	Conceptual representation in the digital twin	Impact on islanding decisions	Battery dispatch implication
Short-horizon photovoltaic overprediction	Rapid cloud movement, irradiance sensor mismatch, weather model delay	Upper-biased generation scenario corrected by real-time photovoltaic measurements	May cause premature islanding with insufficient generation reserve	Requires higher battery reserve before separation and faster discharge response after islanding
Short-horizon photovoltaic underprediction	Conservative irradiance forecast, unexpected cloud clearing	Lower-biased scenario compared with measured ramp-up conditions	May delay islanding even when local adequacy is feasible	Allows more flexible state-of-charge allocation to load restoration

Wind ramp forecast error	Turbulence, local terrain effects, low-resolution wind forecasts	Probabilistic ramp scenarios with confidence bands	May misrepresent post-islanding frequency and power-balance risk	Requires dispatch smoothing and reserve allocation for ramp compensation
Load forecast error during disturbance	Human response, emergency load behavior, building control changes	Priority-weighted demand scenarios by critical and flexible load classes	May distort the estimated load that must be preserved after islanding	Requires adaptive load restoration and possible deferral of noncritical loads
Correlated renewable-load error	Weather-driven coincidence between renewable drop and demand increase	Joint scenarios linking irradiance, temperature, wind, and demand	Increases adequacy risk because generation shortfall and demand increase occur together	Requires stricter pre-islanding state-of-charge thresholds
Forecast horizon drift	Increasing uncertainty over longer look-ahead periods	Time-dependent uncertainty envelope around renewable and load forecasts	Makes delayed islanding decisions less reliable as uncertainty widens	Requires rolling reassessment of recovery margin and dispatch feasibility
Model structural error	Incomplete forecasting model, missing local features, degraded data stream	Bias-tracking module comparing predicted and observed output	Can produce repeated misclassification of islanding readiness	Requires conservative reserve policy until the forecasting model is recalibrated

Battery Dispatch and Recovery Logic

Battery roles in islanded microgrids

Battery energy storage can be conceptualized as the main fast-response actuator that allows the islanded microgrid to absorb disturbances, regulate power balance, and preserve critical loads. Resilient microgrid modeling with digital twins has shown that demand response and renewable coordination can be represented as interacting design elements rather than isolated control functions [20]. In the proposed framework, the battery would provide transition support immediately after islanding, short-term frequency and voltage assistance, and energy-limited recovery capability during the degraded operating phase. Its dispatch logic should therefore be linked to the digital twin’s forecast-error module and resilience decision engine.

Pre-islanding state-of-charge management

Pre-islanding state-of-charge management should be designed to maintain a resilience reserve that is distinct from routine economic scheduling. Renewable-based microgrid energy management using digital-twin and learning-based techniques illustrates how battery decisions can be embedded in a realistic virtual control environment [21]. In this framework, the digital twin would continuously estimate whether the current state of charge is sufficient for transition support, minimum critical-load service, and staged restoration under adverse renewable scenarios. A low state of charge would not automatically prohibit islanding, but it would increase the resilience risk score and may trigger pre-islanding load reduction or charging priority.

Dispatch during islanding transition

During the islanding transition, battery dispatch should be coordinated with converter controls, breaker status, and real-time power imbalance to avoid frequency nadirs and voltage deviations. Enhanced frequency-aware microgrid scheduling under seamless islanding highlights that frequency support from heterogeneous resources must be considered before and during separation [22]. The proposed digital twin would issue a transition dispatch profile that reserves fast battery response for the first seconds of islanded operation while slower resources adjust to the new operating mode. This transition logic would enable the controller to move from grid-following dependence toward islanded stabilization with reduced disruption to critical loads.

Post-islanding load restoration strategy

Post-islanding recovery should prioritize loads according to criticality, available battery energy, renewable uncertainty, and expected restoration time. Distributed risk-limiting load restoration in systems with networked microgrids shows that restoration decisions can be framed as risk-aware allocation problems under network and resource constraints [23]. In the proposed framework, the digital twin would rank restoration blocks, estimate the energy cost of each restoration step, and compare that cost with the battery recovery margin. Critical loads would be restored first, while discretionary or flexible loads would be delayed until renewable forecasts and state-of-charge trajectories indicate sufficient resilience margin.

Coordination with renewable ramping and forecast updates

Battery dispatch recovery should remain adaptive because renewable ramps can either assist recovery or undermine islanded adequacy. A review of forecasting in energy storage applications emphasizes that storage operation benefits when forecast information is explicitly incorporated into dispatch decisions [24]. The proposed framework would therefore update battery setpoints whenever the digital twin detects a meaningful change in renewable forecast error, load behavior, or state-of-charge trajectory. This rolling coordination would allow the battery to shift between stabilization, reserve preservation, renewable smoothing, and load-restoration support as the islanded microgrid evolves.

Figure 3 depicts battery dispatch as a recovery mechanism that begins before islanding, supports transition stability during controlled separation, and continues through staged critical-load restoration under rolling renewable forecast updates.

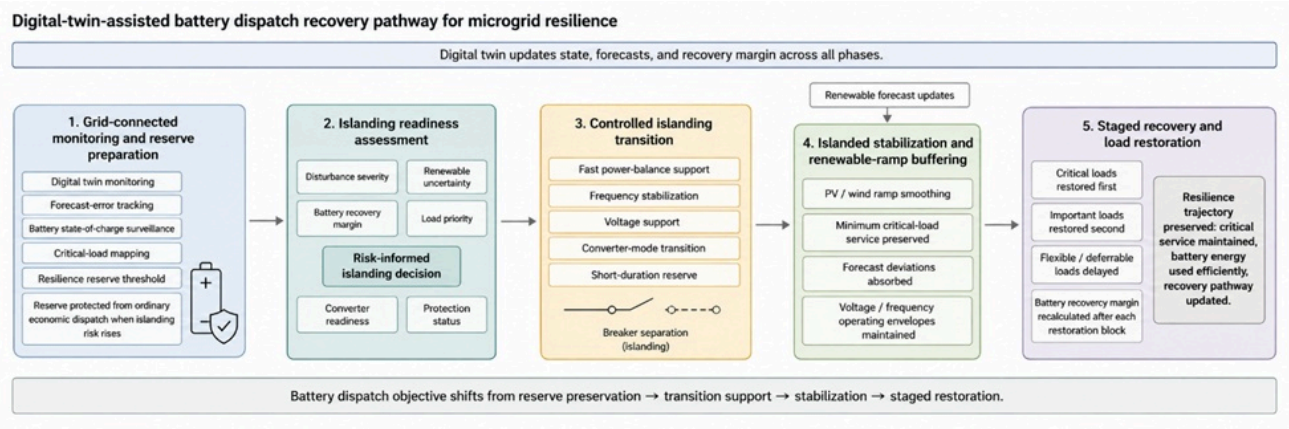


Figure 3. Battery Dispatch Recovery Pathway across Pre-Islanding, Transition, and Post-Islanding Resilience Phases

Conceptual Control Architecture

High-level architecture overview

The proposed architecture can be conceptualized as a layered cyber-physical system that links field sensing, digital twin synchronization, uncertainty modeling, resilience assessment, islanding control, battery dispatch, and operator supervision. Digital twin design studies that combine laboratory-scale validation with large-scale proposals suggest that microgrid twins can be structured as extensible control environments rather than single-purpose models [25]. In this article, the architecture is not intended as an implemented controller but as a design blueprint for future validation. Its core premise is that resilience control improves when islanding and battery recovery are governed by the same synchronized twin state.

Data acquisition and twin synchronization

The data acquisition layer should collect measurements from meters, phasor devices, inverters, battery management systems, protection devices, weather feeds, and controllable loads. Digital twin and artificial-intelligence studies for microgrid prediction show that power generation prediction can be connected to virtual microgrid representations for operational analysis [26]. Within the proposed architecture, these data streams would be checked for latency, quality, and consistency before updating the twin. Synchronization would then support a shared operating picture for disturbance detection, forecast-error assessment, islanding readiness, and battery recovery planning.

Resilience monitoring and decision engine

The resilience monitoring and decision engine would evaluate whether the microgrid is moving toward unacceptable service degradation under current and forecasted conditions. Networked microgrid research emphasizes that resilience, robustness, and efficiency can be strengthened when multiple local systems are coordinated rather than treated as isolated entities [27]. In the proposed framework, the decision engine would calculate a resilience threat state from grid disturbance indicators, renewable uncertainty, battery reserve, load criticality, and islanding feasibility. This state would determine whether the microgrid remains grid-connected, prepares for islanding, executes islanding, or initiates recovery sequencing.

Islanding and battery dispatch coordination

The islanding and battery dispatch coordination layer would convert the resilience decision into physical actions, including breaker commands, converter-mode changes, load-priority enforcement, and battery dispatch profiles. Resilience-oriented microgrid scheduling using robust mixed-integer conic optimization demonstrates that resilience objectives can be embedded into operational scheduling rather than added after the fact [28]. Conceptually, the digital twin would test a candidate islanding action against battery reserve, renewable scenarios, and recovery targets before execution. Once islanded, the same layer would update dispatch as the resilience trajectory changes.

Human-operator interface and override

The human-operator interface should present the digital twin's recommended actions, confidence levels, forecast-error exposure, islanding adequacy, and expected recovery pathway. Systematic reviews of digital twin and artificial-intelligence applications in the energy transition emphasize the importance of linking advanced analytics with operational decision support [29]. In this framework, the operator would retain override authority, especially when cyber anomalies, data quality concerns, or social priorities complicate automated action. Table 3 summarizes the conceptual architecture layers and the information flows that would connect sensing, twin analysis, islanding, battery recovery, and human supervision.

Table 3. Conceptual Control Architecture: Layers, Functions, and Data Flows

Architecture layer	Primary function	Input information	Output information	Resilience-control role

Physical microgrid layer	Operates distributed generation, storage, feeders, switches, loads, and protection devices	Local electrical states, device limits, breaker positions, battery status	Measurements, alarms, and actuator responses	Provides the physical basis for islanding, stabilization, and restoration
Data acquisition layer	Collects and filters operational, weather, load, and asset-condition data	Sensors, meters, inverter telemetry, weather forecasts, battery management data	Validated and time-stamped data streams	Reduces uncertainty caused by poor visibility or delayed measurements
Digital twin synchronization layer	Updates virtual states and reconciles measurements with models	Validated data streams, network model, asset parameters	Synchronized twin state and data-quality flags	Maintains a reliable virtual mirror for decision support
Forecast uncertainty layer	Produces renewable and load uncertainty scenarios	Weather forecasts, historical errors, real-time renewable output, demand trends	Scenario envelopes, confidence levels, and adequacy-risk signals	Links forecast uncertainty to islanding readiness and reserve requirements
Resilience decision layer	Determines operating mode and resilience threat level	Twin state, disturbance indicators, uncertainty scenarios, load priority, battery reserve	Mode recommendation and resilience-risk classification	Selects grid-connected, prepare-to-island, island, or recovery state
Islanding coordination layer	Executes controlled separation and transition sequencing	Mode recommendation, protection status, synchronization checks, dispatch readiness	Breaker commands, converter-mode commands, transition setpoints	Supports intentional and seamless islanding when resilience is threatened
Battery recovery layer	Allocates battery power and energy for stabilization and restoration	State of charge, renewable scenarios, critical-load demand, restoration priorities	Battery dispatch commands and reserve updates	Preserves critical service and manages post-islanding recovery
Operator interface layer	Communicates recommendations, explanations, and override options	Risk classifications, forecast confidence, action plans, data-quality flags	Operator approval, override, or revised operating constraints	Provides accountable supervision of high-impact resilience actions

Resilience Performance Indicators

Resilience metrics for islanded microgrids

Resilience performance indicators should capture degradation, adaptation, and recovery rather than only steady-state reliability. Resilience-oriented operation studies with power-to-hydrogen systems show that resilience can be linked to operational flexibility, backup capability, and post-disturbance service preservation [30]. In the proposed framework, indicators would be calculated by the digital twin before islanding as expected values and after islanding as observed trajectories. This dual use would allow the controller to compare predicted resilience with actual recovery performance.

Load served and critical load preservation

Load served should be measured with explicit priority weighting because preserving critical loads is more important than maximizing undifferentiated energy delivery during severe disturbance. Mobile storage and microgrid resilience studies show that distributed and mobile energy resources can enhance service continuity when they are allocated to vulnerable parts of the distribution system [31]. In the proposed framework, the digital twin would distinguish critical, important, flexible, and deferrable load classes when evaluating battery-supported recovery. This distinction would make resilience assessment consistent with the operational purpose of islanding.

Recovery time and battery utilization

Recovery time should be defined as the interval required to restore a target level of critical service after islanding or disturbance onset. Hybrid stochastic-robust scheduling for resilient microgrids indicates that uncertainty-aware scheduling can support recovery-oriented decisions when demand response and uncertain resources are present [32]. Battery utilization should be measured not only as total energy discharged but also as the effectiveness of discharge in preserving critical service and stabilizing the islanded microgrid. The digital twin could therefore track whether battery energy is being spent on high-resilience actions or consumed by avoidable forecast and dispatch errors.

Forecast quality impact on resilience

Forecast quality should be treated as a resilience performance indicator because inaccurate renewable and load predictions can change islanding timing, reserve adequacy, and recovery feasibility. Reviews of uncertainty models for stochastic optimization in renewable energy applications show that uncertainty representation strongly influences operational decisions under renewable variability [33]. In the proposed framework, the digital twin would compare forecasted and observed renewable output to update confidence levels and resilience margins. Table 4 proposes indicators that connect forecast quality, load preservation, battery use, and control objectives.

Table 4. Resilience Performance Indicators for Digital-Twin-Assisted Microgrid Control

Indicator	Definition	Conceptual measurement method	Link to microgrid control objective
Critical load preservation ratio	Share of priority-weighted critical load served during islanded operation	Compare served critical load with required critical load over the islanding interval	Guides load restoration and battery allocation priorities
Time to controlled islanding	Time between threat detection and completed intentional islanding	Measure from resilience-threat flag to verified islanded operating mode	Evaluates whether the controller separates before upstream disturbance propagates
Transition stability margin	Distance between observed voltage and frequency deviations and allowable limits during islanding	Track nadir, overshoot, settling behavior, and converter response after separation	Assesses whether islanding is seamless enough to preserve service quality
Battery recovery margin	Remaining usable battery energy after satisfying transition and minimum critical-load requirements	Estimate state of charge against forecasted recovery demand and reserve thresholds	Determines whether additional loads can be restored safely
Forecast-error exposure index	Degree to which islanding adequacy depends on uncertain renewable or load forecasts	Compare scenario spread with available dispatch flexibility and battery reserve	Links forecasting quality to islanding readiness and reserve policy

Restoration effectiveness	Amount of priority-weighted service restored per unit of battery energy used	Relate restored load blocks to battery discharge during recovery	Encourages efficient use of limited stored energy
Resilience trajectory deviation	Difference between predicted and observed service-preservation trajectory	Compare digital twin forecast of degradation and recovery with measured operation	Supports learning, recalibration, and future controller improvement
Operator intervention rate	Frequency of human overrides or manual adjustments during resilience events	Record override actions and reasons during islanding and recovery	Reveals whether automation recommendations are trusted and operationally usable

Key Design Considerations

Communication and latency requirements

Communication and latency requirements are central because digital twin-assisted islanding depends on timely sensing, synchronization, and command execution. Frequency-aware seamless islanding research indicates that transition decisions are sensitive to dynamic system behavior, making delayed or inconsistent information problematic for islanding control [22]. The proposed framework should therefore distinguish between fast local controls that must operate autonomously and slower supervisory functions that can be mediated through the twin. A resilient design would use the twin for decision support while ensuring that protection and converter controls remain safe under communication degradation.

Data privacy and twin security

Data privacy and twin security should be treated as design requirements because the digital twin aggregates operational, asset, load, and control information that could expose vulnerabilities. Digital twin applications in energy systems increasingly rely on artificial intelligence and connected data flows, which expands the attack surface for manipulation, inference, or unauthorized control [29]. In the proposed framework, cyber-physical integrity would require authentication, anomaly detection, data validation, and fail-safe operating modes. The twin should also flag when data confidence is too low for autonomous islanding or battery recovery decisions.

Scalability to multi-microgrid systems

Scalability is important because resilience may be improved when neighboring microgrids coordinate resources, exchange support, or form networked islands. Reviews of networked microgrids show that coordinated operation can enhance resilience and robustness while introducing additional control and communication complexity [27]. The proposed architecture could be extended by allowing each microgrid twin to exchange resilience indicators, available reserve, and restoration priorities with neighboring twins. Such coordination would require careful design so that local islanding autonomy is preserved while regional recovery support is enabled.

Regulatory and standardization aspects

Regulatory and standardization aspects should be considered because digital twin-assisted islanding involves protection settings, interconnection rules, operator responsibility, and reconnection procedures. Microgrid protection and synchronization work highlights that seamless transition and grid reconnection require coordinated control schemes that remain compatible with system protection expectations [5]. The framework therefore should be interpreted as a conceptual design that requires further validation against local grid codes, utility operating practices, and safety requirements. Future standards could benefit from resilience indicators that make digital twin recommendations transparent, auditable, and comparable across microgrid deployments.

Conclusion

This article proposed a conceptual framework for digital-twin-assisted microgrid control that integrates resilience-oriented islanding, renewable forecast uncertainty, and battery dispatch recovery. The framework positions the digital twin as a synchronized decision-support environment that continuously monitors microgrid state, evaluates resilience threats, and coordinates control actions across islanding and recovery phases. Its central contribution is the integration of functions that are often treated separately in microgrid control discussions.

The framework conceptualizes islanding as a resilience decision rather than only a protection event. It suggests that islanding should be triggered through combined assessment of disturbance severity, forecast-error exposure, battery reserve, and critical-load preservation. Battery dispatch is treated as a recovery logic that begins before islanding, supports transition stability, and continues through staged restoration.

The proposed architecture offers a design blueprint with layers for data acquisition, twin synchronization, uncertainty modeling, resilience decision-making, islanding coordination, battery recovery, and operator supervision. The four tables clarify the roles of digital twin components, forecast error types, architecture layers, and resilience performance indicators. These elements are intended to support future controller design without claiming empirical validation.

Future research should validate the framework through simulation, controller-in-the-loop studies, hardware-in-the-loop testing, and field demonstrations. Further work should also examine cyber-security, communication latency, interoperability, and human-operator trust in digital twin-assisted resilience control. The framework is expected to help researchers and practitioners design microgrid controllers that are more adaptive, transparent, and recovery-oriented under uncertain renewable and disturbance conditions.

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