

REVIEW

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A Critical Review of Battery Storage Scheduling and Renewable Curtailment Reduction in Active Distribution Networks Using Stochastic and Robust Optimization

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Abstract

Active distribution networks face growing renewable curtailment as distributed photovoltaic and wind generation increasingly encounter voltage, congestion, and flexibility constraints. Battery storage scheduling under uncertainty has become a central operational strategy for absorbing otherwise curtailed energy and improving distribution-level renewable integration. Despite substantial growth in optimization-based storage studies, the literature remains fragmented across stochastic programming, chance-constrained optimization, robust optimization, and distributionally robust formulations. No critical review has systematically compared these paradigms for storage scheduling and curtailment reduction specifically in active distribution networks. This critical review assesses and contrasts stochastic and robust optimization models for battery storage scheduling aimed at reducing renewable curtailment in active distribution networks. It evaluates how these approaches represent uncertainty, network constraints, operational objectives, and implementation readiness. A structured critical review of 27 peer-reviewed journal articles published between 2017 and 2024 was conducted. The analysis focuses on mathematical formulations, uncertainty modeling, storage representation, curtailment objectives, network constraints, and operational applicability. Stochastic models offer strong expected-performance reasoning but often depend on scenario quality and can become computationally demanding. Robust models provide stronger protection against adverse uncertainty realizations but may become conservative when uncertainty sets are poorly calibrated, while gaps remain in real-time scheduling, multi-service operation, degradation modeling, and field validation. The choice between stochastic and robust optimization depends on operator risk preference, data availability, computational resources, and distribution network complexity. Hybrid, data-driven, and implementation-oriented methods offer promising future pathways for reducing renewable curtailment through battery storage scheduling.

Keywords Stochastic optimization, Battery storage scheduling, Renewable curtailment, Active distribution networks, Robust optimization, Critical review

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Introduction

Renewable penetration in distribution networks has shifted curtailment from a transmission-level balancing issue to a local operational challenge shaped by feeder congestion, voltage rise, and limited flexibility. Studies on curtailment mitigation show that battery storage can absorb excess wind or photovoltaic generation when network export capacity is

constrained, as demonstrated in wind-connected systems [1] and high-photovoltaic distribution grids [2]. The literature demonstrates that curtailment is not merely wasted energy but also a symptom of insufficient coordination between generation, network capacity, and flexible resources. This review therefore treats curtailment reduction as a distribution-system scheduling problem rather than as a simple surplus-energy management issue.

Battery energy storage has emerged as one of the most technically flexible tools for mitigating renewable curtailment because it can shift energy across time, support voltage control, and respond to operational constraints faster than many conventional assets. Mobile and stationary storage studies show that storage placement, timing, and charging decisions strongly influence how much curtailed renewable energy can be recovered [3, 4]. However, storage is not a free flexibility resource, because charging efficiency, depth of discharge, cycle aging, and capacity limits shape its operational value. A critical limitation in the literature is that curtailment reduction is often optimized without sufficiently integrating battery degradation, market participation, and network operation into a single decision framework [5].

Uncertainty is central to battery scheduling because renewable generation, load demand, market prices, and network conditions are not known perfectly ahead of time. Stochastic active distribution network models have used scenarios to represent uncertain photovoltaic generation, wind output, and load variation [6], while reliability-aware chance-constrained formulations have introduced probabilistic feasibility requirements for storage sizing and operation [7]. Yet the practical usefulness of these approaches depends heavily on the quality of probability distributions, scenario construction, and available operational data. This review argues that uncertainty modeling should be judged not only by mathematical elegance but also by whether distribution operators can trust and implement the resulting schedules.

Stochastic and robust optimization have become the two dominant paradigms for managing uncertainty in battery scheduling and renewable integration, but they embody different assumptions about risk and information. Stochastic programming evaluates expected outcomes over scenarios, as seen in two-stage and hybrid scheduling studies [8], whereas robust optimization protects against uncertain realizations within predefined uncertainty sets, as reflected in adjustable robust scheduling for hybrid distribution networks [9]. Distributionally robust optimization occupies an intermediate position by protecting against ambiguity in probability distributions, which has been applied to active distribution networks and storage sizing problems [10, 11]. The key critical issue is not which paradigm is universally superior, but which paradigm is appropriate for a given operational context, data environment, and risk tolerance.

This review critically examines battery storage scheduling and renewable curtailment reduction in active distribution networks using stochastic and robust optimization approaches. It draws on 27 peer-reviewed journal articles from 2017 to 2024, including studies on storage scheduling, curtailment mitigation, active distribution network planning, robust uncertainty handling, and broader reviews of optimization under uncertainty [12, 13]. The contribution is threefold: it clarifies how storage and curtailment are modeled, compares stochastic and robust paradigms, and identifies gaps between academic formulations and implementation-ready distribution operation. Rather than presenting new experiments or numerical results, the review synthesizes the literature to support methodological evaluation and future research design.

Review Scope

The scope of this review is limited to optimization-based battery storage scheduling for renewable curtailment reduction in active distribution networks. Included studies address stationary or mobile battery systems, distribution-level renewable hosting, curtailment mitigation, stochastic programming, chance constraints, robust optimization, and distributionally robust optimization [4, 10]. The review also considers related active distribution network functions, including voltage control, congestion management, flexible demand, and ancillary service provision when they are modeled jointly with storage operation [5, 14]. This boundary is necessary because curtailment reduction in active distribution systems depends on the interaction between storage schedules, feeder constraints, uncertainty, and operational flexibility.

The review excludes purely deterministic storage scheduling studies unless they directly support comparison with uncertainty-aware formulations, and it does not consider transmission expansion, wholesale-only market clearing, or non-optimization curtailment control as primary topics. General energy storage reviews are used only where they help clarify storage valuation, control functions, or market roles, such as the assessment of storage applications and markets [15]. Microgrid control literature is considered only when it informs uncertainty-aware storage scheduling principles relevant to distribution networks [16]. This focus prevents the article from becoming a broad storage review and keeps the analysis centered on stochastic and robust optimization for curtailment reduction.

Battery Storage Scheduling Background

Roles of battery storage in distribution networks

Battery storage performs multiple roles in active distribution networks, including renewable absorption, peak shaving, energy arbitrage, voltage support, congestion relief, backup provision, and ancillary service participation. Strategic integration studies show that distributed batteries can provide ancillary services while also supporting local network operation [5], and coordinated planning work has examined battery placement alongside soft open points, demand response, and conservation voltage reduction [14]. For curtailment reduction, the most important role is temporal flexibility: batteries charge during renewable surplus and discharge when network or demand conditions permit. A key limitation is that many studies optimize one dominant role while underrepresenting conflicts among curtailment recovery, market revenue, degradation cost, and local grid support.

Modeling storage in optimization

Battery storage is typically modeled through state-of-charge balance equations, charging and discharging power limits, round-trip efficiency, capacity constraints, and terminal state requirements. More advanced formulations incorporate electrothermal-aging coupling, showing that schedules that appear economically optimal may accelerate battery degradation if thermal and cycling effects are ignored [17]. Studies on optimal siting and sizing also demonstrate that storage value depends on location, feeder loading, and renewable penetration rather than only on battery capacity [18]. A key limitation is that degradation-aware modeling remains unevenly integrated into curtailment-focused optimization, even though cycle life directly affects the long-term feasibility of aggressive curtailment absorption strategies.

Market and regulatory context

Battery storage scheduling is increasingly shaped by market signals, ancillary service opportunities, tariff structures, and regulatory rules governing distributed energy resources. Reviews of storage applications and markets show that battery value depends on stacked services rather than a single revenue stream, including energy arbitrage, reserve provision, congestion relief, and reliability support [15]. However, active distribution networks often lack fully developed local flexibility markets that reward curtailment reduction or feeder-level voltage support. This creates a mismatch between optimization models that assume coordinated scheduling authority and real-world settings where ownership, market access, and regulatory incentives may fragment decision-making.

Renewable Curtailment Problem

Causes of curtailment at distribution level

Renewable curtailment at the distribution level occurs when local generation exceeds the network's ability to absorb, export, or redistribute power while maintaining voltage and thermal limits. High photovoltaic penetration can cause voltage rise and reverse power flow, while wind-rich areas may experience export constraints that require curtailment unless storage or flexible demand is available [2]. Active distribution network planning studies show that curtailment is also linked to the limited coordination of active network management schemes under uncertain operating conditions [19].

The literature demonstrates that curtailment is therefore not only a renewable generation problem but also a network flexibility, forecasting, and operational coordination problem.

Impact and cost of curtailment

Curtailment reduces the economic value of renewable assets, lowers clean-energy utilization, and can weaken the business case for distributed generation investment. Timescale analysis of storage for curtailment reduction shows that the storage duration needed depends on whether curtailment is driven by short intraday peaks, prolonged seasonal surplus, or network bottlenecks [20]. From an environmental perspective, curtailed renewable output may force greater reliance on fossil generation elsewhere in the system, although the magnitude depends on the broader generation mix and dispatch context. A key limitation in many optimization studies is that curtailment is treated as a penalty term without sufficiently linking it to emissions, investor risk, local reliability, or distribution planning costs.

Role of optimization in curtailment reduction

Optimization models reduce curtailment by coordinating when batteries charge, discharge, reserve capacity, or support network constraints under uncertain renewable and load conditions. Two-stage battery sizing and scheduling studies show that optimization can allocate storage capacity to reduce wind curtailment while balancing cost and operational feasibility [1]. Mobile battery fleet studies further demonstrate that spatial flexibility can capture curtailed renewable energy across multiple network locations, although such models require stronger logistical and operational assumptions [4]. This review argues that optimization is most valuable when it captures the trade-off between curtailment recovery, network security, battery health, and computational implementability.

Stochastic Optimization Review

Two-stage stochastic programming

Two-stage stochastic programming is widely used for storage scheduling because it separates first-stage planning or commitment decisions from second-stage recourse actions after uncertainty is realized. Hybrid stochastic and robust planning of distributed battery storage has demonstrated how storage investment and flexible energy management can be coordinated under uncertain renewable and demand conditions [8]. Two-stage stochastic scheduling has also been applied in hybrid AC/DC distribution networks with energy storage and converter operation, illustrating how network structure complicates scenario-based decision-making [21]. A key limitation is that two-stage formulations may oversimplify sequential operational decisions when storage schedules must be updated repeatedly across short dispatch intervals.

Chance-constrained models

Chance-constrained optimization addresses uncertainty by allowing a controlled probability of constraint violation, which can be useful when strict deterministic feasibility is too conservative. Reliability-aware battery sizing methods for islanded microgrids show how probabilistic constraints can align storage design with reliability targets while acknowledging renewable and load uncertainty [7]. In distribution networks, chance constraints are attractive because voltage and power balance requirements may not need to be satisfied for every extreme scenario if acceptable risk thresholds are defined. However, their practical application depends on credible probability distributions, and poorly estimated violation probabilities can create schedules that appear reliable mathematically but are fragile operationally.

Scenario generation and reduction methods

Scenario generation and reduction are central to stochastic optimization because they determine how uncertainty in renewable output, load, prices, and network states is represented. Monte Carlo-based approaches have been used to schedule batteries under distribution network uncertainty [22], while stochastic allocation studies for high-renewable

distribution networks show how uncertainty representation affects storage placement and dispatch decisions [23]. The literature demonstrates that scenario richness improves realism but increases computational burden, creating a trade-off between statistical representation and solvability. Few studies provide enough evidence that their scenarios remain valid under changing renewable penetration, evolving demand profiles, or extreme weather conditions.

Limitations and applicability

Stochastic optimization is valuable when credible historical data, probabilistic forecasts, and computational resources are available, but its applicability weakens when data are sparse or distributional assumptions are unstable. Reviews of power system optimization under uncertainty emphasize that stochastic methods can produce efficient expected outcomes, yet they often face scalability challenges as network detail, time resolution, and uncertainty dimensions increase [12]. Data-driven and machine-learning-assisted studies suggest that renewable curtailment utilization can be improved through predictive methods coupled with storage planning [24], but they also increase dependence on data quality and model transparency. This review argues that stochastic optimization is best suited to operators who can maintain forecasting infrastructure and accept probabilistic rather than worst-case guarantees.

Robust Optimization Review

Adjustable robust optimization

Adjustable robust optimization (ARO) allows decision variables to adapt after the realization of uncertainty, providing recourse for battery dispatch in active distribution networks. Two-stage affinely adjustable robust scheduling has been applied to hybrid AC/DC distribution networks to coordinate sources, storage, and load under uncertainty [9]. The literature demonstrates that ARO can improve operational flexibility compared with static robust formulations while maintaining worst-case guarantees. However, a key limitation is that affine decision rules may oversimplify nonlinear battery behavior, and scalability can become an issue in large networks with many uncertain parameters.

Distributionally Robust Optimization (DRO)

Distributionally robust optimization considers ambiguity in probability distributions, ensuring solutions are robust against distributional deviations. Moment-based and Wasserstein-metric DRO formulations have been employed for battery storage sizing and curtailment reduction under uncertain wind and solar generation [10, 11]. These approaches mitigate overfitting to historical scenarios and provide protection against unexpected variations in renewable output. Yet, the conservativeness of DRO depends strongly on the size and shape of the ambiguity set, and overly cautious formulations can limit energy arbitrage opportunities or reduce storage utilization efficiency.

Uncertainty set design

The choice of uncertainty sets determines the trade-off between robustness and performance. Budget-of-uncertainty and data-driven sets have been widely studied in the context of distribution network storage scheduling [25]. Properly designed uncertainty sets capture the range of possible renewable generation and load fluctuations without being excessively conservative. Many studies show that poor calibration of uncertainty sets leads either to over-conservatism, which reduces curtailment recovery, or under-coverage, which risks network constraint violations [11]. This review emphasizes that uncertainty set design is both a technical and practical challenge, linking modeling choices directly to operational outcomes.

Conservativeness and tractability

Robust optimization provides protection against extreme events but can be computationally intensive, especially when multiple batteries, network constraints, and multi-period operations are considered [8, 9]. Adjustable and distributionally robust formulations improve tractability relative to full robust models but may still require scenario approximation or

relaxation techniques. The literature demonstrates that conservativeness is often necessary for reliability but can reduce expected performance, and tractable formulations may sacrifice modeling fidelity. Operators must therefore balance computational feasibility, robustness level, and practical implementability when selecting robust methods [17, 25].

Critical Comparison

Modeling fidelity and assumptions

Stochastic models explicitly use probabilistic forecasts to optimize expected outcomes, which allows detailed representation of renewable variability and network response [8, 21]. Robust optimization assumes uncertainty within predefined sets and seeks solutions that remain feasible under worst-case realizations [9, 11]. The literature demonstrates that stochastic models better capture expected cost and curtailment performance under realistic scenario distributions, while robust models provide operational guarantees but may be overly conservative if uncertainty sets are mischaracterized [12, 13]. A key observation is that neither paradigm alone perfectly balances fidelity, computational feasibility, and operational practicality in real-world distribution networks.

Computational performance and scalability

Stochastic optimization generally incurs high computational cost, particularly with large scenario trees or fine time resolution, limiting applicability to small-to-medium networks or requiring scenario reduction techniques [22, 23]. Robust optimization can offer more tractable formulations through adjustable rules and linearized uncertainty sets, but conservativeness increases with problem size and complexity [9, 25]. Comparative studies indicate that both approaches face scalability challenges, with stochastic models excelling in expectation-based performance and robust models providing stronger worst-case reliability, albeit at the cost of potentially slower solution times [8, 17].

Performance metrics and operational impact

In terms of curtailment reduction, stochastic models achieve lower expected curtailment by exploiting probabilistic forecasts, while robust models ensure feasibility across uncertain conditions [1, 4, 24]. Cost impacts follow a similar pattern: stochastic scheduling often lowers expected operational cost but may expose the network to rare violations, whereas robust approaches prevent worst-case overloads but may incur higher expected cost due to conservative charging/discharging schedules [2, 7]. Reliability metrics favor robust methods, whereas expected energy capture and market participation favor stochastic optimization. This nuanced trade-off underscores the need for context-specific assessment.

Figure 1 shows a conceptual overview of battery storage scheduling in active distribution networks for renewable curtailment reduction. It illustrates energy flows from photovoltaic and wind generation into distribution feeders, the absorption of excess energy by battery storage, stochastic scenario-based scheduling, robust worst-case optimization, and multi-service stacking including voltage support and ancillary services. Degradation-aware scheduling and real-time adaptive feedback are also highlighted.

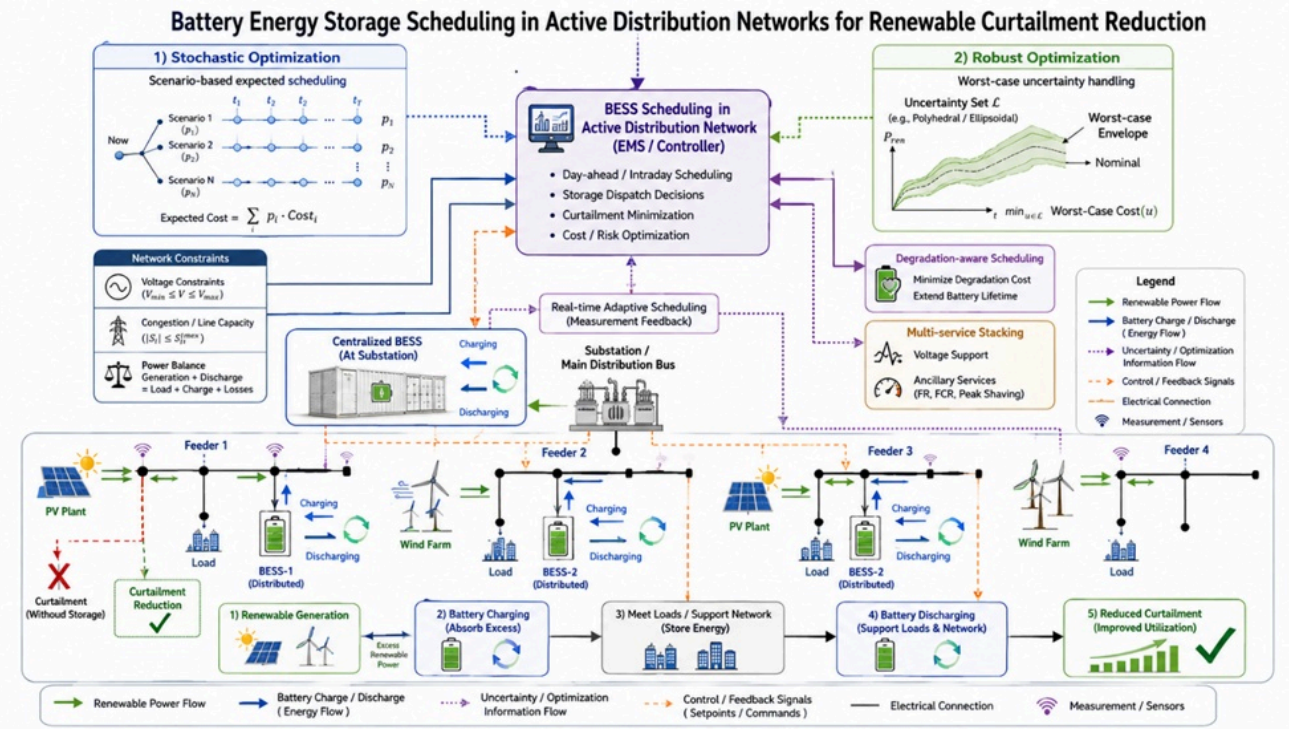


Figure 1. Conceptual diagram of battery storage scheduling in active distribution networks for renewable curtailment reduction. The figure illustrates energy flows from photovoltaic and wind generation into distribution feeders, battery storage absorption,

Table 1 compares stochastic and robust optimization for battery scheduling and curtailment reduction, summarizing their differences in uncertainty modeling, data needs, computational burden, conservativeness, scalability, real-time suitability, and performance. It highlights that stochastic optimization is scenario-based and typically achieves better expected performance but with higher computational effort, while robust optimization uses uncertainty sets to ensure stronger worst-case reliability at the cost of increased conservativeness and potentially lower average utilization.

Table 1. Comparative Synthesis of Stochastic vs. Robust Optimization for Battery Scheduling and Curtailment Reduction

Criterion	Stochastic Optimization	Robust Optimization
Uncertainty Handling	Probabilistic scenarios; expectation-based	Worst-case / uncertainty set; adjustable or DRO
Data Requirements	Requires accurate probability distributions and historical data	Requires bounds or ambiguity set; less sensitive to distribution accuracy
Computational Load	High with large scenario trees; may need scenario reduction [22, 23]	Moderate to high; adjustable formulations improve tractability [9, 25]
Conservativeness	Moderate; balances expected performance and risk	High if uncertainty sets are large; may reduce expected utilization
Scalability	Challenging for large networks or multi-period problems	Better with linearized adjustable rules; may still degrade with network size
Real-Time Suitability	Limited by scenario generation and solution time	More suitable with pre-computed robust schedules

Reported Performance	Lower expected curtailment, lower expected cost	Higher reliability, reduced worst-case violations
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Suitability for different network and market contexts

Stochastic models are particularly suitable for networks with reliable forecasting, abundant data, and markets that reward expected energy utilization or arbitrage [14, 23]. Robust optimization is favored where operators prioritize worst-case reliability, regulatory compliance, or risk-averse management of feeder constraints [9, 10]. The literature demonstrates that hybrid approaches may be desirable in mixed contexts, where operators face both market-based incentives and strict network security requirements [8, 25]. Decision-makers must assess operational priorities, computational resources, and acceptable conservativeness when choosing the appropriate optimization paradigm.

Technical and Operational Gaps

Real-time and adaptive scheduling gaps

Few studies have addressed real-time updating of battery schedules in response to fast-changing renewable output or load conditions [22, 24]. The literature demonstrates that precomputed schedules often fail to capture intraday variations, leading to missed curtailment recovery opportunities. Adaptive or receding-horizon methods are scarce, and real-time implementability is limited by computational requirements and communication latency in active distribution networks.

Multi-service stacking and battery degradation

Multi-service scheduling, which combines curtailment reduction, voltage support, and market participation, is underrepresented in both stochastic and robust literature [5, 15]. Moreover, degradation-aware optimization that explicitly accounts for cycle life, thermal constraints, and efficiency losses is unevenly applied, reducing confidence that aggressive curtailment strategies are sustainable. Existing models often optimize only a single objective, ignoring long-term battery health and revenue stacking opportunities.

Network constraint integration

The inclusion of AC power flow, OLTC, capacitor banks, and reactive power constraints varies widely across studies [6, 8, 17]. Some models simplify network physics to maintain tractability, potentially overestimating curtailment recovery or underestimating overload risk. This limitation affects operational realism and the transferability of simulation results to actual distribution feeders.

Table 2 summarizes key technical and operational gaps in current research on battery scheduling, highlighting limitations in real-time adaptability, multi-service coordination, degradation-aware modeling, and network constraint fidelity, all of which significantly affect curtailment reduction performance, asset valuation accuracy, and system-level operational reliability.

Table 2. Technical and Operational Gaps in Current Research

Gap Category	Description	Affected Outcome	Current Research Coverage	Priority for Future Work
Real-Time Scheduling	Lack of adaptive or receding-horizon methods	Missed curtailment recovery	Low [22, 24]	High

Multi-Service Integration	Single-objective focus; neglects stacking of ancillary services	Suboptimal battery utilization and revenue	Medium [5, 15]	High
Degradation-Aware Modeling	Limited inclusion of cycle aging, thermal effects	Overestimation of battery lifespan and value	Low [17]	High
Network Constraint Fidelity	Simplified power flow and feeder models	Over/underestimation of curtailment reduction	Medium [6, 8]	Medium

Data availability and validation deficits

Data scarcity remains a key challenge, especially for probabilistic forecasts and real feeder conditions [12, 19]. Validation studies are limited, and few optimization models have been tested with real distribution network operations. The lack of validated datasets constrains confidence in proposed scheduling frameworks, reducing the practical impact of academic research on operational decision-making.

Future Pathways

Hybrid stochastic-robust models

Combining stochastic and robust paradigms offers a path to balance expected performance with worst-case guarantees [8, 9]. Hybrid models can use stochastic scenario-based planning while applying robust constraints for critical feeders or peak events, potentially enhancing operational resilience without excessive conservativeness. This approach is promising but requires careful calibration of scenarios and uncertainty sets.

Data-driven and learning-based optimization

Machine learning and data-driven methods can enhance both stochastic and robust scheduling by improving forecasts, generating realistic scenarios, and approximating complex system responses [23, 24]. Integration with optimization frameworks allows dynamic adjustment to renewable fluctuations and load patterns, but model transparency, data quality, and operational trust remain critical challenges.

Multi-objective and multi-stakeholder frameworks

Future frameworks should incorporate multiple objectives, including curtailment reduction, cost minimization, reliability, and battery longevity, while also considering different stakeholders such as distribution operators, prosumers, and regulators [14, 15]. Multi-objective formulations can reveal trade-offs and support participatory decision-making. Implementation complexity, coordination, and computation are primary barriers.

Table 3 summarizes the main future research pathways for battery scheduling and curtailment reduction, highlighting hybrid stochastic-robust modeling, data-driven optimization, multi-objective decision frameworks, and regulatory and market design developments, along with their enabling methods, expected impacts, key implementation barriers, and indicative time horizons for practical deployment.

Table 3. Future Research Pathways and Implementation Roadmap

Pathway	Key Enabling Methods	Expected Impact	Potential Barriers	Time Horizon
Hybrid Stochastic-	Scenario-based planning	Balanced performance and	Scenario calibration,	Medium

Robust Models	+ robust constraints	worst-case protection	computational load	
Data-Driven Optimization	Machine learning, predictive analytics	Improved forecast accuracy, adaptive scheduling	Data quality, transparency, trust	Medium-Long
Multi-Objective Frameworks	Multi-objective optimization, stakeholder input	Trade-off analysis, participatory decision-making	Coordination complexity, computation	Long
Regulatory & Market Design	Incentive structures, flexibility markets	Align scheduling with operational incentives	Policy lag, market readiness	Long

Regulatory and market design innovations

Policy changes, local flexibility markets, and incentive alignment are essential to translate optimization results into operational practice [5, 10, 15]. Regulatory frameworks should support multi-service stacking, reward curtailment reduction, and allow adaptive battery operation while safeguarding network security. Literature shows that without enabling policy, methodological advances remain underutilized in real distribution networks.

Conclusion

Battery storage scheduling and renewable curtailment reduction in active distribution networks remain critical research areas. The review demonstrates that stochastic optimization excels in expected performance, while robust optimization provides worst-case guarantees. Comparative assessment highlights trade-offs in fidelity, conservativeness, computational demand, and operational applicability.

Significant gaps persist, including real-time adaptability, multi-service integration, degradation-aware modeling, and realistic network constraint representation. Data scarcity and limited validation further constrain operational implementation.

Targeted future research should explore hybrid stochastic-robust models, learning-based optimization, multi-objective frameworks, and regulatory innovations to enhance curtailment reduction in operational distribution networks. Real-world pilots and regulatory alignment will be critical for translating optimization models into practice.

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