

SYSTEMATIC REVIEW

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A Systematic Review of Uncertainty-Aware Stochastic Optimization for Demand Response, DER Coordination, and Flexibility Provision in Active Distribution Networks

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Abstract

Active distribution networks increasingly rely on stochastic optimization to manage uncertainties arising from renewable generation, flexible demand, distributed storage, electric vehicles, and local energy markets. These uncertainties affect voltage quality, congestion, operational cost, reliability, and the value of flexibility. This systematic review categorizes and evaluates uncertainty-aware stochastic optimization techniques for demand response, DER coordination, and flexibility provision in active distribution networks. It focuses on methodological transparency, thematic synthesis, and identification of research gaps. A PRISMA-guided systematic review of 31 peer-reviewed journal articles published from 2017 to 2023 was conducted. A structured search, screening, eligibility assessment, and data extraction process was used to organize the evidence. The review maps dominant stochastic frameworks, including two-stage stochastic programming, chance-constrained optimization, robust-stochastic formulations, and distributionally robust optimization. Five synthesis tables are used across the full manuscript to summarize study selection, article characteristics, method taxonomies, application mappings, and research gaps. Stochastic optimization supports secure and efficient operation of active distribution grids, but important gaps remain in scalability, real-world validation, interoperability, and regulatory integration. The review outlines an agenda for more adaptive, transparent, and implementation-ready optimization methods.

Keywords Stochastic optimization, Demand response, Distributed energy resources, Flexibility provision, Active distribution network, Systematic review

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Introduction

Active distribution networks are increasingly exposed to uncertainty because photovoltaic generation, flexible demand, electric vehicles, battery storage, and local energy transactions introduce variability at the grid edge. Demand response has therefore shifted from a passive load-management mechanism to an operational resource that can be scheduled under uncertain renewable output and consumption patterns [1]. In distribution-level applications, stochastic optimization provides a structured way to represent uncertain operating states while preserving network constraints such as voltage limits, congestion boundaries, and resource availability [2].

The reviewed literature shows that uncertainty-aware optimization has diversified into two-stage stochastic programming, chance-constrained optimization, robust-stochastic hybrids, scenario-based probabilistic scheduling, and distributionally robust optimization. Two-stage models are commonly used when day-ahead decisions must be protected against uncertain real-time outcomes, as seen in microgrid and DER scheduling studies [3]. Chance-constrained formulations instead emphasize probabilistic feasibility, particularly where renewable generation uncertainty must be balanced against reserve, voltage, or peer-to-peer trading constraints [4].

This systematic review synthesizes journal articles published between 2017 and 2023 that address stochastic optimization for demand response, DER coordination, and flexibility provision in active distribution networks. It treats demand response, storage, electric vehicles, distributed generation, and flexibility markets as interconnected elements rather than isolated topics, reflecting the integrated framing adopted in local flexibility market studies [5]. The manuscript proceeds from methodology and literature characterization to method-level synthesis, application-domain analysis, uncertainty modeling, algorithmic assessment, research gaps, and future directions.

Motivation and Review Questions

The motivation for this review is the rapid expansion of uncertainty-aware optimization studies that use overlapping terminology but differ substantially in modeling scope, uncertainty representation, and operational assumptions. Some studies emphasize demand response and renewable uncertainty in distribution networks [6], while others focus on congestion management, flexibility markets, peer-to-peer coordination, or multi-microgrid scheduling [7]. This diversity creates a need for systematic classification because the same label, such as stochastic scheduling or flexibility optimization, may refer to different uncertainty models, decision stages, and grid-service objectives.

The review is guided by four questions: which stochastic optimization frameworks dominate the literature, how are demand response and DERs modeled as flexible resources, how are uncertainties represented, and which gaps limit practical deployment in active distribution networks. These questions are informed by evidence that DER scheduling, local flexibility trading, and distribution congestion management are often studied separately despite sharing common uncertainty and coordination challenges [8]. The review therefore evaluates not only individual model families but also their ability to support integrated flexibility provision across distribution-level operational and market contexts [9].

Systematic Review Methodology

Search strategy

The search strategy targeted peer-reviewed journal articles published from 2017 to 2023 in power systems, smart grids, energy systems, and distribution-network optimization. Search strings combined terms such as stochastic optimization, demand response, distributed energy resources, active distribution networks, flexibility provision, DSO coordination, probabilistic scheduling, and distributionally robust optimization, reflecting the terminology used in representative demand-response and flexibility-market studies [2]. The search focused on journals including IEEE Transactions on Smart Grid, IEEE Transactions on Power Systems, Applied Energy, International Journal of Electrical Power & Energy Systems, Electric Power Systems Research, Sustainable Energy, Grids and Networks, Renewable and Sustainable Energy Reviews, and related energy journals.

Eligibility criteria

Articles were included when they proposed, reviewed, or critically assessed uncertainty-aware optimization methods for demand response, DER coordination, flexibility provision, active distribution network operation, or closely related microgrid and local-energy-market applications. Studies were retained when uncertainty was explicitly modeled through scenarios, probabilistic constraints, robust sets, ambiguity sets, forecasting-informed scheduling, or stochastic market-

clearing formulations, as illustrated by probabilistic microgrid scheduling and distribution-level demand response work [10]. Books, theses, standards, websites, policy reports, conference papers, non-peer-reviewed material, and studies outside the 2017–2023 publication window were excluded.

Study selection process

The study selection process followed a PRISMA-inspired flow that began with database identification, duplicate removal, title and abstract screening, full-text assessment, and final inclusion. Articles were excluded when they lacked explicit uncertainty treatment, did not address distribution-level or DER-related operation, or focused on transmission-only planning without demand response or flexible resources. The final corpus of 31 studies was selected because it collectively covered demand response optimization [11], DER and microgrid coordination [12], flexibility markets [13], peer-to-peer trading [14], and uncertainty-aware distribution-network operation [15].

Figure 1 summarizes the PRISMA-guided study selection process used to identify the final corpus of 31 studies included in the qualitative synthesis.

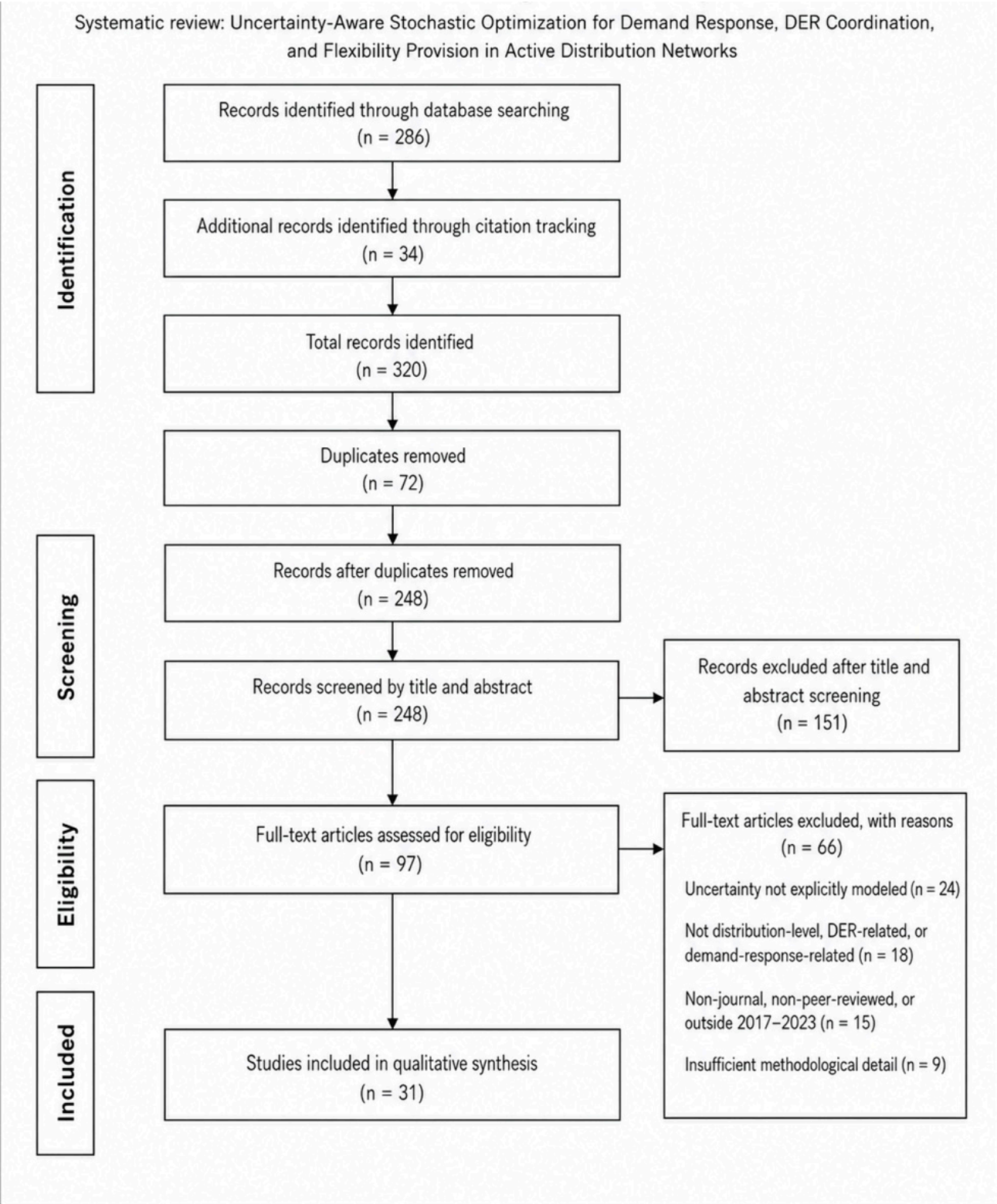


Figure 1. PRISMA 2020 Flow Diagram of Study Identification, Screening, Eligibility, and Inclusion

Data extraction and synthesis

For each included article, data were extracted on publication year, journal, application domain, uncertainty source, optimization framework, decision horizon, DER type, flexibility service, and validation context. The synthesis used

thematic coding rather than statistical meta-analysis because the included studies differ in objectives, test systems, modeling assumptions, and performance metrics. **Table 1** reports the PRISMA study selection flow used to transparently connect the initial record pool to the 31 included studies, following the systematic logic used to structure review articles on demand response and renewable integration [16].

Table 1. PRISMA Study Selection Flow

Stage	Count
Records identified through database searching	286
Additional records identified through citation tracking	34
Total records identified	320
Duplicates removed	72
Records screened by title and abstract	248
Records excluded after title and abstract screening	151
Full-text articles assessed for eligibility	97
Full-text articles excluded because uncertainty was not explicitly modeled	24
Full-text articles excluded because the application was not distribution-level, DER-related, or demand-response-related	18
Full-text articles excluded because they were non-journal, non-peer-reviewed, or outside 2017–2023	15
Full-text articles excluded because they lacked sufficient methodological detail	9
Studies included in qualitative synthesis	31

Overview of Included Studies

Bibliometric and publication trends

The included studies show sustained publication activity from 2017 to 2023, with early emphasis on demand response, renewable uncertainty, and microgrid scheduling, followed by growing attention to local flexibility markets and distributionally robust formulations. Applied Energy, International Journal of Electrical Power & Energy Systems, IEEE Transactions on Smart Grid, IEEE Transactions on Power Systems, and Sustainable Energy, Grids and Networks are strongly represented, indicating that the topic sits between power-system operation, energy optimization, and smart-grid market design. The publication trajectory also reflects the movement from microgrid-centered uncertainty scheduling [17] toward integrated flexibility provision involving DSOs, aggregators, and network-constrained DER portfolios [18].

Thematic distribution

The studies were classified into three broad themes: demand response optimization, DER and microgrid coordination, and flexibility provision through local markets or distribution-network services. Demand response studies emphasize price-based, incentive-based, and controllable-load flexibility under renewable and load uncertainty [19], whereas DER coordination studies focus on PV, batteries, multi-energy resources, electric vehicles, and networked microgrids [20]. **Table 2** summarizes the included studies in terms of year, application, uncertainty type, optimization method, and test-system context, showing that active distribution networks are often represented through benchmark feeders, modified distribution systems, microgrid clusters, or market simulation environments [21].

Table 2. Summary of Included Studies

Study ID	Year	Application	Uncertainty Type	Optimization Method	Test System
[1]	2018	Renewable generation management and demand response	Renewable generation and load	Decentralized stochastic optimization	Distribution network case study
[19]	2022	Demand response with distribution locational marginal pricing	PV generation	Stochastic demand response optimization	Distribution network with PV
[6]	2021	Industrial microgrid demand response	PV output and battery cost	Uncertainty-aware scheduling	Industrial microgrid
[22]	2019	Flexible-resource demand response	Load and resource availability	Predictive stochastic control	Active distribution network
[2]	2018	DSO flexibility requests	DER availability and market bids	Optimization-based flexibility clearing	Local flexibility market case
[5]	2018	Aggregator flexibility services	DER flexibility and market uncertainty	Market-design optimization	Distribution-level flexibility market
[13]	2023	Technical virtual power plant flexibility	DER flexibility capability	Local flexibility market optimization	Distribution-level VPP framework
[8]	2021	Congestion management using energy hubs	DER output and demand	Network-constrained optimization	Distribution network with energy hubs
[3]	2018	Networked microgrid energy management	Renewable generation and demand	Two-stage stochastic programming	Networked microgrids
[23]	2018	Microgrid energy management	Renewable generation and load	Robust two-stage optimization	Microgrid test system
[10]	2017	Networked microgrid scheduling	Renewable generation, load, and price	Probabilistic scheduling with demand response	Networked microgrids
[17]	2019	Interconnected microgrid management	Renewable generation and demand	Hierarchical stochastic energy management	Interconnected microgrids
[24]	2020	Isolated renewable multi-microgrid operation	Renewable generation and demand response	Uncertainty-aware energy management	Isolated multi-microgrid
[12]	2022	Microgrid energy management	Renewable generation, storage, and demand	Optimal scheduling under uncertainty	Microgrid
[25]	2023	Unbalanced active distribution network DER operation	Correlated uncertainty sources	Two-stage stochastic programming	Unbalanced distribution network
[15]	2023	Active distribution network operation	Renewable generation and network states	Chance-constrained optimization	Active distribution feeder
[4]	2021	Peer-to-peer joint energy	Renewable generation	Chance-constrained	Peer-to-peer energy

		and reserve market		market optimization	market
[14]	2021	Interconnected microgrid energy trading	Renewable generation and demand	Data-driven distributionally robust optimization	Interconnected microgrids
[26]	2023	Transactive energy among microgrids and smart parking lots	Market and DER uncertainty	Moment-based distributionally robust optimization	Networked microgrids and parking lots
[7]	2019	Decentralized distribution flexibility market design	DER flexibility and local demand	Decentralized market optimization	Distribution flexibility market
[18]	2022	Peer-to-peer flexibility for voltage control	Flexible resource availability	Peer-to-peer flexibility optimization	Low-voltage distribution network
[9]	2020	Deliverable flexibility and regulation capacity	DER availability and network constraints	Coordinated flexibility optimization	Distribution network
[27]	2021	Flexibility-constrained active distribution operation	Flexible demand and DER uncertainty	Flexibility-constrained scheduling	Active distribution network
[21]	2019	Congestion management through demand response	Demand response participation and network loading	Optimization-based congestion management	Active distribution network
[28]	2022	Virtual storage plants for congestion and frequency support	Storage availability and service demand	Flexibility scheduling optimization	Distribution-connected virtual storage
[20]	2022	Multi-energy microgrid operation	Renewable generation, load, and energy prices	Scenario-based two-stage stochastic optimization	Multi-energy microgrid
[29]	2020	Multi-energy systems and microgrids	Renewable generation and demand	Robust optimization	Multi-energy microgrid
[11]	2019	Demand response optimization review	Demand response modeling uncertainty	Review and classification	Power-system demand response literature
[16]	2017	Demand response barriers and enablers	Consumer, technical, and market uncertainty	Review and classification	Smart-grid demand response literature
[30]	2018	Smart-grid demand response review	Demand response participation and system conditions	Review and synthesis	Smart-grid environment
[31]	2020	Variable renewable integration review	Renewable generation variability	Review of integration technologies	Renewable-energy integration literature

Review of Stochastic Optimization Frameworks

Two-stage and multi-stage stochastic programming

Two-stage stochastic programming is one of the most visible frameworks in the reviewed literature because it separates first-stage commitments from second-stage recourse actions under uncertain operating scenarios. In networked microgrids, this structure allows energy purchases, storage commitments, or DER schedules to be selected before uncertainty is realized, while corrective dispatch and demand response actions are optimized after renewable generation or load becomes known [3]. More recent active distribution network studies extend this logic to unbalanced feeders and correlated uncertainties, showing that two-stage formulations can capture both temporal decisions and network feasibility when DER portfolios become more heterogeneous [25].

Chance-constrained and robust-stochastic models

Chance-constrained models are used when operators need probabilistic guarantees that voltage, reserve, or market-clearing constraints will be satisfied despite uncertainty. Peer-to-peer energy and reserve market work illustrates how chance constraints can embed renewable uncertainty while maintaining service reliability [4], and active distribution network formulations use similar ideas to represent risk-limited operation under uncertain injections [15]. Robust-stochastic models, by contrast, place stronger emphasis on worst-case or ambiguity-aware feasibility, which is useful in microgrid energy management when historical data are limited or renewable forecast errors are difficult to characterize precisely [23].

Distributionally robust optimization

Distributionally robust optimization appears in the reviewed literature as a response to the limitations of assuming that probability distributions are perfectly known. In peer-to-peer and interconnected microgrid trading, data-driven ambiguity sets allow operators to hedge against distributional error while retaining less conservative behavior than classical robust optimization [14]. Moment-based formulations extend this idea by using limited statistical information to coordinate transactive energy among networked microgrids, smart parking lots, and distribution systems, and Table 3 compares this method family with the broader stochastic optimization approaches identified in the review [26].

Table 3. Comparative Taxonomy of Stochastic Optimization Approaches

Approach	Key Features	Typical Applications	Strengths	Limitations
Two-stage stochastic programming	First-stage scheduling with second-stage recourse across scenarios	DER scheduling, microgrid operation, demand response aggregation	Captures corrective actions and expected-cost trade-offs	Scenario growth can create high computational burden
Multi-stage stochastic programming	Sequential decisions across multiple uncertainty realizations	Rolling DER coordination and storage dispatch	Represents temporal adaptation more realistically	Often difficult to solve for large distribution networks
Chance-constrained optimization	Constraints satisfied with specified probability levels	Voltage regulation, reserve scheduling, peer-to-peer markets	Balances risk and operational efficiency	Requires distributional assumptions or tractable approximations
Robust-stochastic optimization	Combines scenarios with worst-case uncertainty protection	Microgrid scheduling and conservative DER operation	Improves feasibility under forecast error	Can be conservative and sensitive to uncertainty-set design

Distributionally robust optimization	Optimizes against probability distributions within ambiguity sets	Transactive energy, peer-to-peer trading, data-driven scheduling	Handles imperfect distributional knowledge	Ambiguity-set calibration remains challenging
Scenario-based probabilistic optimization	Uses generated or sampled scenarios to represent uncertainty	Multi-energy microgrids and renewable scheduling	Flexible and intuitive for mixed uncertainty sources	Performance depends on scenario quality and reduction methods
Decentralized and market-based stochastic optimization	Coordinates actors through prices, bids, or local market mechanisms	Flexibility markets, aggregators, DSO services	Supports privacy and distributed ownership	Market rules and network constraints can be difficult to align

Application Domains: Demand Response, Der Coordination, Flexibility

Demand response optimization

Demand response optimization is treated in the reviewed literature as both a cost-reduction mechanism and a distribution-network operational resource. Decentralized renewable generation management studies show that flexible demand can absorb renewable variability when customer response is coordinated with uncertain supply conditions [1]. Industrial microgrid work further demonstrates that demand response is often modeled alongside PV and battery operation, where uncertainty affects both load shifting and storage dispatch decisions [6]. Review studies also indicate that demand response effectiveness depends not only on optimization design but also on customer participation, incentive structures, automation, and institutional barriers [11].

Distributed energy resource coordination

DER coordination studies typically combine PV, batteries, electric vehicles, energy hubs, multi-energy resources, and controllable loads into integrated scheduling problems. Predictive control of flexible resources in active distribution networks shows that DER coordination must account for operational constraints as well as short-term uncertainty in resource availability [22]. Isolated and interconnected multi-microgrid studies extend this coordination challenge by coupling renewable generation, storage, and demand response under uncertain local conditions [24]. Virtual storage and multi-energy system studies indicate that aggregated DERs can provide distribution support, congestion relief, and system-level services when optimization models capture temporal coupling and flexibility limits [28].

Flexibility provision and market integration

Flexibility provision is increasingly modeled as a market-mediated service in which aggregators, virtual power plants, peer-to-peer participants, or local energy communities offer controllable injections, demand reductions, or reserve capacity to distribution operators. Local flexibility market studies show that DER portfolios can respond to DSO requests when optimization models represent bids, technical constraints, and service deliverability [5]. Decentralized flexibility market design adds that market rules must be compatible with network constraints because flexibility that is economically attractive may not be physically deliverable at a constrained node [7]. Table 4 maps the reviewed application domains to the stochastic method families most often used for demand response, DER coordination, and flexibility services.

Table 4. Application Domain – Method Matrix

Application domain	Two-stage stochastic programming	Chance-constrained optimization	Robust-stochastic optimization	Distributionally robust optimization	Scenario-based probabilistic optimization	Decentralized and market-based optimization
Demand Response	Frequently used for day-ahead scheduling with recourse-based load adjustment	Used when service delivery or network feasibility must meet probability limits	Used where uncertain participation or forecast error requires conservative schedules	Emerging use for uncertain customer response and price distributions	Common for renewable-linked load shifting and incentive-based response	Used for aggregator bidding and customer-side coordination
DER Coordination	Common for PV, battery, EV, and microgrid scheduling under renewable uncertainty	Used for voltage, reserve, and feeder-security constraints	Common in microgrid and multi-energy scheduling with uncertain renewable output	Used for data-driven coordination when probability distributions are uncertain	Very common for PV, load, storage, and price uncertainty	Used for distributed ownership, energy hubs, and virtual power plants
Flexibility Services	Used for pre-commitment and real-time activation of flexibility	Used for deliverability, reserve, and reliability-constrained services	Used where DSOs require conservative service availability	Used in transactive and peer-to-peer settings with uncertain market behavior	Used to evaluate service availability across plausible operating states	Dominant in local flexibility markets, peer-to-peer trading, and DSO–aggregator coordination

Uncertainty Modeling in the Reviewed Literature

Scenario-based and probabilistic approaches

Scenario-based and probabilistic approaches dominate studies that represent renewable generation, load, prices, and DER availability through sampled or forecast-derived operating states. Probabilistic scheduling of networked microgrids illustrates how demand response and uncertain renewable output can be integrated through scenario-informed operational decisions [10]. Multi-energy microgrid studies similarly use scenario-based two-stage optimization to represent correlated uncertainty across electricity, heat, and energy prices [20]. These approaches are flexible and interpretable, but the review identifies persistent concerns about scenario quality, scenario reduction, and the limited comparability of results across studies.

Robust and distributionally robust uncertainty sets

Robust and distributionally robust uncertainty modeling is used when decision makers seek protection against forecast errors without relying on a single known probability distribution. Robust optimization for multi-energy systems and microgrids shows that uncertainty sets can improve operational security, although overly conservative set design may reduce economic efficiency [29]. Data-driven distributionally robust peer-to-peer energy trading uses ambiguity sets to hedge against distributional misspecification while retaining market participation and network operation objectives [14]. Moment-based distributionally robust formulations extend this logic by using limited statistical descriptors, which is

attractive in distribution systems where high-quality operational datasets may be incomplete or commercially sensitive [26].

Solution Algorithms and Computational Aspects

Decomposition and heuristic methods

The reviewed studies use a range of computational strategies, including centralized mixed-integer optimization, decentralized coordination, hierarchical scheduling, market-clearing formulations, and decomposition-inspired methods. Hierarchical energy management for interconnected microgrids illustrates how layered optimization can reduce coordination complexity while preserving interactions among local resources [17]. Local flexibility market and aggregator studies also imply decomposition needs because DSOs, aggregators, customers, and DER owners make decisions with different information, objectives, and privacy requirements [13]. However, the review identifies limited consistency in reporting convergence behavior, computational burden, solver settings, and sensitivity to scenario size.

Scalability and real-time capability

Scalability remains a central barrier because active distribution networks combine mixed-integer decisions, nonlinear or linearized power-flow constraints, multi-period coupling, and uncertainty representations. Flexibility-constrained active distribution network scheduling shows that operational detail can improve realism but also increases model complexity when flexible resources must satisfy both economic and technical constraints [27]. Chance-constrained active network formulations similarly highlight the trade-off between probabilistic security and computational tractability in distribution-level operation [15]. The review finds that many studies demonstrate feasibility on benchmark or modified test systems, but fewer provide evidence of real-time applicability in large, data-rich, multi-actor distribution grids.

Cross-Cutting Analysis and Research Gaps

Figure 2 integrates the reviewed stochastic optimization frameworks, application domains, uncertainty representations, and implementation gaps that shape the transition from academic models to utility-ready flexibility coordination.

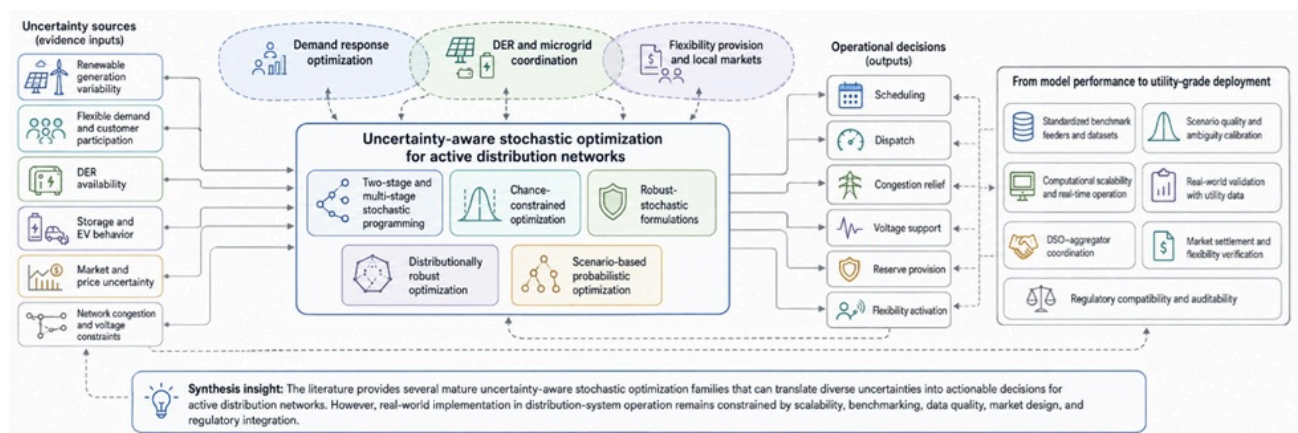


Figure 2. Evidence-to-Implementation Map of Uncertainty-Aware Stochastic Optimization in Active Distribution Networks

Comparative performance and benchmarking gaps

A major cross-cutting gap is the absence of standardized benchmarks that allow fair comparison among stochastic programming, chance-constrained, robust, and distributionally robust formulations. Studies on demand response optimization often use different assumptions about customer flexibility, tariffs, uncertainty sources, and baseline behavior,

making cross-study comparison difficult [30]. DER coordination studies likewise vary in feeder models, storage constraints, renewable profiles, and risk metrics, which limits the ability to identify when a more complex uncertainty model is genuinely superior to a simpler scenario-based formulation [25]. The review therefore identifies benchmarking as a methodological gap rather than merely a reporting issue.

Real-world validation and data limitations

Real-world validation is limited because many studies rely on stylized networks, simulated customers, representative DER profiles, or modified test feeders. Reviews of demand response barriers emphasize that technical optimization results may not transfer directly to practice when consumer acceptance, automation infrastructure, privacy, and market access are weak [16]. Renewable integration reviews similarly show that variability management requires not only optimization but also forecasting, control infrastructure, regulatory support, and operational coordination [31]. The review therefore identifies a gap between mathematically sophisticated scheduling models and field-ready tools that can operate under imperfect data, uncertain customer response, and changing distribution-network conditions.

Regulatory and market design gaps

Regulatory and market design gaps are especially visible in flexibility provision studies because distribution-level services require clear rules for procurement, activation, verification, settlement, and coordination with wholesale markets. Deliverable flexibility studies show that flexibility must be evaluated against network constraints and service obligations, not simply aggregated as available capacity [9]. Peer-to-peer flexibility trading for voltage control further suggests that local transactions can support distribution operation, but only if market mechanisms internalize physical limits and avoid creating new congestion or voltage violations [18]. **Table 5** maps the main research gaps to future directions, suggested methodologies, and potential policy or industry relevance.

Table 5. Research Gaps and Future Directions

Gap	Future Direction	Suggested Methodology	Potential Policy/Industry Impact
Lack of standardized benchmarks	Develop open benchmark feeders, DER portfolios, uncertainty datasets, and flexibility-service definitions	Shared test cases with common metrics for cost, risk, voltage, congestion, emissions, and computation time	Improves comparability and accelerates adoption by DSOs, aggregators, and vendors
Limited real-world validation	Test stochastic optimization in pilots, digital twins, and operational planning tools	Hardware-in-the-loop, field trials, rolling-horizon simulations, and utility data partnerships	Reduces implementation risk and supports evidence-based procurement of flexibility
Weak modeling of customer behavior	Integrate behavioral uncertainty and participation dynamics into demand response models	Data-driven elasticity estimation, probabilistic participation models, and privacy-preserving learning	Improves reliability of demand response as a grid resource
Scenario quality and ambiguity calibration	Establish transparent methods for scenario generation, reduction, and ambiguity-set design	Forecast-error analytics, Wasserstein or moment-based ambiguity sets, and sensitivity analysis	Supports auditable risk management and regulatory confidence
Limited DSO–TSO coordination	Couple distribution flexibility with system-level balancing, congestion, and reserve needs	Multi-level stochastic optimization and coordinated market-clearing models	Enables flexibility stacking while reducing conflicting activations

Computational scalability constraints	Design adaptive, decomposed, and distributed optimization architectures	ADMM, progressive hedging, Benders decomposition, surrogate models, and rolling-horizon control	Makes uncertainty-aware optimization more practical for large active distribution networks
Unclear market settlement and verification	Link optimization outputs to measurable flexibility delivery and baseline rules	Measurement and verification protocols, settlement-aware optimization, and contract-based modeling	Supports transparent local flexibility markets and customer trust

Future Research Directions

Scalable and adaptive stochastic optimization

Future research should prioritize scalable stochastic optimization methods that adapt to changing uncertainty distributions, DER availability, and network operating conditions. Two-stage and chance-constrained formulations provide useful foundations, but active distribution grids require rolling, adaptive, and data-updating versions that can operate close to real time [3]. Decomposition, learning-assisted scenario management, and privacy-preserving distributed optimization are promising directions for coordinating large numbers of customer-owned resources without relying on full centralized information [1]. Such methods should report computational performance consistently so that scalability claims can be evaluated across comparable network and market settings.

Integration of multi-energy and transactive systems

A second research direction is the integration of multi-energy systems, transactive energy, peer-to-peer trading, and local flexibility markets within unified stochastic optimization frameworks. Multi-energy microgrid studies show that electricity, heat, storage, and renewable uncertainty can be co-optimized, but these models are often separated from distribution-level market settlement and DSO service procurement [20]. Peer-to-peer and distributionally robust trading studies indicate that market participants can be coordinated under uncertainty, yet further work is needed to connect trading outcomes with voltage control, congestion relief, and flexibility verification [4]. Future models should therefore represent both physical deliverability and economic incentives across electricity, thermal, mobility, and storage resources.

Standardization and benchmarking

Standardization and benchmarking are essential for transforming uncertainty-aware optimization from a research literature into an operational toolkit. Demand response reviews show that inconsistent assumptions about baselines, participation, incentives, and evaluation metrics hinder cumulative learning [11]. Flexibility market studies similarly require common definitions of service products, activation windows, locational granularity, and performance verification if optimization results are to inform regulation or procurement [2]. Future research should therefore establish open datasets, common uncertainty models, reproducible solver settings, and benchmark feeders that allow rigorous comparison among stochastic, robust, and distributionally robust approaches.

Limitations of the Review

Search and selection constraints

This review is limited by its reliance on 31 peer-reviewed journal articles published between 2017 and 2023, which means that some relevant conference papers, technical reports, standards, and pilot-project documents were intentionally excluded. The selection criteria favored studies with explicit uncertainty-aware optimization content, so broader work on deterministic DER operation, power-flow control, or market design without stochastic treatment was outside the review

scope [21]. Although this improves methodological focus, it may underrepresent practical implementation knowledge that appears first in utility demonstrations or regulatory proceedings. The review should therefore be interpreted as a synthesis of peer-reviewed academic literature rather than a complete inventory of industry practice.

Rapid evolution of the field

The field is evolving quickly as DER penetration, electrification, digitalization, and flexibility-market experimentation continue to expand. Studies published near the end of the review window already show movement toward data-driven ambiguity sets, peer-to-peer flexibility, and more integrated market-operation models [26]. Because new developments after 2023 are not included, emerging work on artificial intelligence-assisted stochastic optimization, real-time flexibility platforms, and large-scale DSO–TSO coordination may not be reflected. This temporal boundary is necessary for systematic review transparency, but it also means the findings represent a structured snapshot rather than a final assessment of the field.

Conclusion

This systematic review synthesized uncertainty-aware stochastic optimization methods for demand response, DER coordination, and flexibility provision in active distribution networks. The review identified two-stage stochastic programming, chance-constrained optimization, robust-stochastic formulations, distributionally robust optimization, and scenario-based probabilistic scheduling as the main methodological families. Across the included studies, uncertainty modeling is central to making flexible resources operationally useful rather than merely theoretically available.

The evidence suggests that the field has matured from isolated demand response and microgrid scheduling problems toward more integrated formulations involving active distribution networks, aggregators, peer-to-peer trading, virtual power plants, and local flexibility markets. At the same time, important challenges remain in computational scalability, benchmark comparability, ambiguity calibration, customer-behavior modeling, and validation with real operating data. These limitations prevent many proposed methods from moving directly into utility-grade planning or operational environments.

Future progress depends on methods that are scalable, adaptive, transparent, and compatible with regulatory and market implementation. Stronger links among optimization theory, distribution-system operation, customer participation, and flexibility-market design are needed to make uncertainty-aware scheduling dependable in practice. The most useful next generation of research will combine rigorous stochastic modeling with reproducible benchmarks, field validation, and implementation pathways for DSOs, aggregators, and flexibility providers.

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