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A Risk-Aware Optimization Model for Low-Carbon Flexibility Markets Under Renewable Forecast Errors, Prosumer Non-Compliance, and Network Constraints

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Abstract

Low-carbon flexibility markets are becoming important tools for coordinating distributed energy resources, electric vehicles, storage, and responsive demand. Their practical value depends on how well they manage renewable forecast errors, uncertain prosumer behavior, and distribution-network constraints. This article develops a risk-aware optimization model for local flexibility market clearing under renewable forecast uncertainty, prosumer non-compliance, and feeder operating limits. The purpose is to reduce severe cost, carbon, and reliability outcomes rather than optimizing only average performance. The proposed model combines probabilistic renewable uncertainty, statistical prosumer compliance behavior, linearized distribution-network limits, and a conditional value-at-risk representation. The clearing problem is structured as a tractable optimization model suitable for commercial solvers. The model procures low-carbon flexibility while limiting exposure to delivery shortfalls and network infeasibility. The case study compares the proposed risk-aware clearing approach with deterministic and risk-neutral alternatives. The framework provides a practical risk-management tool for flexibility market operators. It supports reliable low-carbon dispatch while accounting for imperfect forecasts, incomplete prosumer delivery, and feeder constraints.

Keywords Risk-aware optimization, Low-carbon flexibility market, Renewable forecast error, Prosumer non-compliance, Network constraints, Conditional value-at-risk

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Introduction

Low-carbon flexibility markets allow distribution system operators and aggregators to procure demand response, storage dispatch, electric vehicle charging adjustment, and distributed generation support as alternatives to carbon-intensive balancing actions. Market-based scheduling and dispatch frameworks show that distributed energy resources can provide operational flexibility when bids, activation rules, and system needs are coordinated [1]. Local market designs also show that aggregators can provide multiple flexibility services at distribution level, making flexibility procurement relevant for congestion relief, balancing support, and renewable integration [2].

A central limitation of deterministic flexibility clearing is that scheduled response often differs from realized physical response. Optimization models for distribution-system flexibility requests demonstrate that aggregated resources can satisfy grid needs under idealized assumptions, but practical outcomes depend on forecast quality and operational

uncertainty [3]. Distribution-level congestion markets further show that flexibility must be cleared against local feeder conditions rather than treated as a uniform system-wide commodity [4].

Recent flexibility-market literature emphasizes decentralized coordination, transparent clearing, and the connection between market bids and physical network feasibility. Decentralized market designs can improve scalability and participant autonomy, but they also increase exposure to uncertain local prices, renewable output, and delivered response [5]. Reviews of local flexibility markets identify market-clearing design, network representation, and uncertainty modeling as central challenges for implementation [6].

The low-carbon objective adds another risk dimension because flexibility shortfalls may force the operator to rely on higher-emission balancing resources. Field evidence from local flexibility markets shows that demand-side resources can be mobilized, but delivery depends on participant availability and operating conditions [7]. Procurement studies similarly show that market efficiency depends not only on expected cost but also on how infeasibility, reserve needs, and uncertainty are handled [8].

This article develops a risk-aware stochastic clearing model for a local low-carbon flexibility market that explicitly accounts for renewable forecast errors, prosumer non-compliance, and distribution-network limits. Network-aware clearing and flexibility-bidding models provide the foundation for embedding feeder constraints into market decisions [9]. Centralized and distributed flexibility-service optimization motivates the integrated treatment of market clearing, delivery uncertainty, and operational feasibility [10].

Low-Carbon Flexibility Market Problem

Market structure and participants

The proposed market is operated by a local market operator acting on behalf of a distribution system operator, with aggregators submitting flexibility offers from prosumers, storage, electric vehicles, photovoltaic inverters, and controllable loads. Hierarchical energy and flexibility trading models show that local coordination must distinguish between wholesale participation, distribution congestion relief, and end-user flexibility provision [11]. In the proposed setting, the operator clears upward and downward flexibility at feeder locations while respecting participant availability, accepted bid conditions, and physical grid feasibility.

Flexibility products and carbon objectives

The market procures active-power reduction, active-power increase, reactive-power support, and time-shifted energy services. Fair and efficient distribution-level flexibility markets require allocation rules that avoid discriminatory dispatch while preserving economic efficiency [12]. The low-carbon objective is represented by favoring flexibility actions that accommodate renewable generation, reduce curtailment, and limit reliance on carbon-intensive backup actions.

Sources of uncertainty

The model considers renewable generation forecast errors, uncertain prosumer delivery, and network-state uncertainty caused by uncertain nodal injections. Day-ahead local flexibility markets for active and reactive power show that linearized network limits can be embedded into clearing, but feasibility depends on realized operating conditions [13]. This means that accepted flexibility must be treated as uncertain delivered capability rather than guaranteed physical response.

Need for risk management

Risk management is required because a low expected-cost solution may still expose the market operator to severe adverse outcomes. Distributionally robust chance-constrained approaches show that flexibility provision in active

distribution networks can be formulated to control uncertainty-driven violations [14]. The proposed model therefore incorporates conditional value-at-risk to penalize severe flexibility shortfalls, carbon-intensive recourse, and feeder-security exposure.

Renewable Forecast Error Model

Probabilistic forecast framework

Renewable generation is represented through a probabilistic forecast rather than a single expected value. Network-aware flexibility-request models show that local market clearing must distinguish between forecasted injections used for scheduling and realized injections that affect feeder operation [15]. The forecast error is treated as a technology-specific random deviation whose spread and asymmetry depend on weather conditions, forecast horizon, and renewable type.

Error distribution fitting

Forecast errors are fitted using empirical and technology-specific distributions instead of assuming one universal error shape. Grid-impact-aware transmission and distribution coordination models show that information sharing affects flexibility procurement efficiency, which motivates using forecast-error models that can be updated with improved local data [16]. Photovoltaic uncertainty is represented with cloud-sensitive asymmetric errors, while wind uncertainty is represented with ramp-sensitive and heavy-tailed behavior.

Spatiotemporal correlations

The scenario model preserves correlations among nearby renewable units and across consecutive market intervals. Uncertainty-aware trading models for congestion and imbalance services show that local flexibility markets must consider joint realization patterns when several feeder areas exchange services [17]. The model therefore retains dependence across location, technology, and time so that adverse renewable conditions are not underestimated.

Scenario generation

The renewable uncertainty model generates a finite set of representative operating scenarios from fitted forecast-error behavior. Chance-constrained stochastic market formulations show that scenario design must balance tractability with adequate coverage of adverse operating conditions [18]. The following table summarizes the renewable forecast-error assumptions used in the case study and explains how each uncertainty source affects market clearing.

Table 1. Renewable Generation Forecast Error Characterization and Its Implications for Market Clearing

Renewable source	Forecast setting	Error characterization	Bias tendency	Variability	Tail behavior	Correlation treatment	Market impact
Rooftop photovoltaic	Near-term operation	Empirical residual distribution	Mild underproduction tendency	Moderate	Cloud-driven underproduction tail	Strong within neighboring feeder areas	Flexibility shortfall and voltage uncertainty
Rooftop photovoltaic	Forward scheduling	Smoothed empirical distribution	Stronger underproduction tendency	High	Weather-regime dependent tail	Moderate across nearby nodes	Higher reserve procurement need

Community photovoltaic	Forward scheduling	Scenario-block residuals	Underproduction tendency	High	Ramp-related tail	Correlated with rooftop photovoltaic	Congestion and curtailment exposure
Small wind	Near-term operation	Mixture-based residuals	Nearly balanced	Moderate	Ramp-sensitive two-sided tail	Weakly related to photovoltaic output	Balancing flexibility requirement
Small wind	Forward scheduling	Weather-conditioned residuals	Mild overproduction tendency	Very high	Heavy lower and upper tails	Persistent over time	Tail-risk exposure during low-wind conditions
Hybrid renewable portfolio	Forward scheduling	Joint scenario distribution	Portfolio-smoothed tendency	Moderate to high	Diversified but non-Gaussian tail	Cross-technology dependence retained	Lower average imbalance with remaining tail risk

Prosumer Non-Compliance Model

Behavioral sources of non-compliance

Prosumer non-compliance occurs when accepted flexibility is not fully delivered because of comfort preferences, mobility needs, appliance availability, communication failures, or strategic withdrawal. Demand response uncertainty studies emphasize that observed response can differ materially from contracted response and should be modeled probabilistically in operational decisions [19]. In this article, each accepted flexibility commitment is adjusted by a random compliance factor representing the delivered share of the accepted service.

Statistical modeling of response uncertainty

Each prosumer class is assigned a bounded compliance distribution reflecting its historical response reliability. Residential demand-management research shows that uncertainty in household behavior can affect aggregate feasibility even when individual deviations appear small [20]. The model represents partial underdelivery and complete non-response separately so that both gradual behavioral deviation and abrupt activation failure influence clearing decisions.

Incentive-dependence

Compliance is modeled as conditional on incentive level, activation duration, participant comfort constraints, and market stress. Robust and chance-constrained formulations for uncertain load-side reserves show that demand-side uncertainty should be linked to reserve availability rather than treated as fixed capacity [21]. In the proposed model, higher incentives improve expected response, while longer activations and stressful operating conditions increase the likelihood of underdelivery.

Impact on market clearing

Non-compliance changes the clearing problem because the operator must procure enough accepted flexibility to satisfy risk-adjusted realized needs. Load-ensemble control in chance-constrained optimal power flow demonstrates that aggregate demand flexibility can be coordinated under uncertainty, but reliability depends on probabilistic availability [22]. The following table summarizes the prosumer compliance assumptions used in the case study and links each class to its clearing consequence.

Table 2. Prosumer Compliance Assumptions and Their Impact on Market-Clearing Outcomes

Prosumer class	Flexibility action	Non-compliance likelihood	Expected delivery quality	Underdelivery pattern	Main correlation driver	Market-clearing consequence
Residential heating and cooling	Load reduction	Moderate	Good but comfort-limited	Gradual underdelivery with rebound	Outdoor temperature and comfort preference	Additional reserve needed during peak periods
Residential electric vehicle	Charging delay	Moderate to high	Variable	Delayed or incomplete response	Departure-time uncertainty	Higher recovery risk later in the schedule
Home battery	Discharge support	Low	High	Limited by stored energy	State of charge	Effective hedge against renewable forecast error
Commercial heating and cooling	Load reduction	Moderate	Good	Occupancy-sensitive underdelivery	Occupancy and indoor-air requirements	Reliable peak flexibility with rebound risk
Small industrial load	Process shifting	Low	High	Schedule-limited response	Production rigidity	High-value but less frequently available flexibility
Photovoltaic inverter	Reactive support	Low	Very high	Headroom-limited response	Available inverter capacity	Voltage-risk reduction during renewable surplus
Community storage	Charge or discharge	Very low	Very high	Control-availability limitation	Aggregator communication and charge state	Primary hedge for risk-aware clearing

Network Constraints

Distribution network model

The distribution feeder is represented as a radial operating system containing loads, renewable units, prosumers, storage devices, and line segments. Energy and reserve dispatch models with distributionally robust joint chance constraints show that uncertainty-aware optimization must preserve feasibility across coupled operating constraints [23]. The market model therefore maps accepted flexibility actions into feeder injections before assessing voltage and line-flow feasibility.

Voltage and congestion limits

Voltage magnitudes must remain within acceptable operating bounds, and branch flows must remain below thermal limits under the considered uncertainty representation. Distributionally robust planning with risk constraints shows that explicit

risk limits can reduce exposure to rare but costly operating violations [24]. In the proposed model, violation penalties are reserved for emergency recourse, while normal clearing decisions are designed to remain feeder-feasible.

Linearization for market integration

The feeder model uses a linearized power-flow representation so that market clearing remains computationally tractable. Stochastic microgrid optimization studies show that linearized uncertainty-aware formulations can represent grid-service requirements while remaining suitable for solver-based implementation [25]. This approximation links nodal flexibility actions to voltage and congestion outcomes without requiring a nonlinear clearing model.

Impact of flexibility dispatch on grid states

Flexibility dispatch can improve or worsen feeder states depending on its location, direction, and timing. Sensitivity analysis of local flexibility markets under forecast error shows that clearing outcomes can change significantly when realized renewable output differs from forecasts [26]. The proposed model internalizes these impacts by co-optimizing flexibility acceptance, expected delivery, emergency recourse, feeder feasibility, and tail-risk exposure.

Risk-Aware Formulation

Decision variables and sets

The market-clearing formulation determines which flexibility offers are accepted, how much low-carbon flexibility is scheduled, how recourse actions are activated under uncertainty, and how emergency penalties are assigned when adverse realizations occur. Risk-aware dispatch studies show that renewable uncertainty and reserve uncertainty should be represented jointly when market outcomes depend on both energy and balancing feasibility [27]. In the proposed model, the decision structure separates first-stage market commitments from scenario-dependent recourse so that accepted bids are economically binding while realized delivery remains uncertain.

Deterministic market clearing model

The deterministic benchmark clears flexibility using expected renewable production, expected prosumer response, and nominal feeder conditions. Local flexibility market studies show that deterministic clearing can be economically efficient when uncertainty is small, but it can underestimate the operating cost of infeasible or underdelivered flexibility [6]. This benchmark minimizes procurement cost and carbon-related recourse cost subject to bid limits, market balance, and network feasibility under expected operating conditions.

Stochastic extension with scenarios

The stochastic extension evaluates each accepted market schedule across renewable and compliance scenarios. Scenario-based uncertainty-aware trading has been shown to improve congestion and imbalance management when flexibility delivery and renewable output are not known at the clearing stage [17]. In this article, each scenario contains a renewable realization, a prosumer delivery realization, and the resulting feeder state, allowing the model to value flexibility not only by price but also by reliability under adverse operating conditions.

Conditional value-at-risk integration

Conditional value-at-risk is introduced to penalize severe outcomes in the upper tail of the system-loss distribution. Chance-constrained and distributionally robust market models demonstrate that expected-cost optimization alone may fail to protect against rare but costly operating states [18]. The proposed loss definition combines flexibility shortfall, carbon-intensive recourse, and network-security penalties, so the risk term directly targets the operational consequences that matter to a low-carbon market operator.

Linearization of risk constraints

The conditional value-at-risk component is written in a deterministic equivalent form that can be handled by a commercial optimization solver. Distributionally robust chance-constrained formulations show that risk and reliability constraints can be reformulated into tractable optimization structures under appropriate assumptions [14]. In the proposed formulation, auxiliary variables represent excess loss beyond a selected risk threshold, enabling the market operator to tune risk aversion without abandoning linear market-clearing logic.

Complete mixed-integer linear formulation

The complete optimization model minimizes procurement cost, expected carbon recourse, and tail-risk exposure while enforcing bid feasibility, balance requirements, compliance-adjusted delivery, and linearized feeder constraints. Stochastic microgrid and flexibility-service optimization studies support the use of mixed-integer linear formulations when uncertainty, flexibility activation, and network limits must be coordinated in one operational model [25]. The model produces accepted bids, scheduled low-carbon flexibility, scenario-dependent corrective actions, and risk prices that reveal where uncertainty is most costly to the distribution system.

Figure 1 illustrates the proposed risk-aware market-clearing architecture, showing how renewable forecast uncertainty, prosumer delivery uncertainty, feeder operating limits, and conditional value-at-risk are integrated to produce reliable low-carbon flexibility procurement decisions.

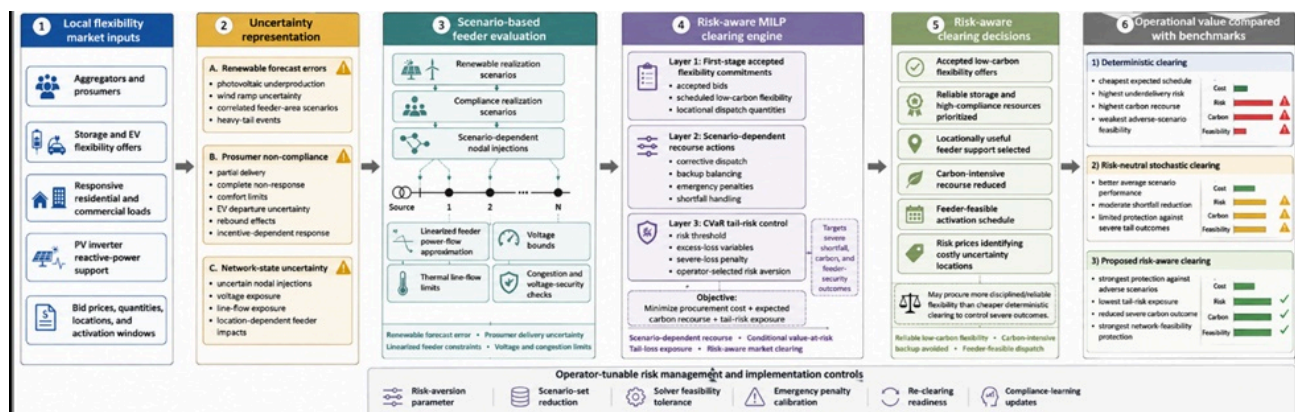


Figure 1. Risk-aware low-carbon flexibility market clearing under renewable forecast errors, prosumer non-compliance, and distribution-network constraints

Solution Method

Solver selection and configuration

The deterministic equivalent is solved as a mixed-integer linear optimization problem using a commercial solver with presolve, branch-and-bound, and feasibility-tolerance controls. Centralized and distributed optimization studies for aggregated flexibility services show that solver-based formulations are suitable for distribution-level market clearing when the network model is linearized and scenario sets are controlled [10]. The solver objective includes market procurement, carbon recourse, and risk exposure, while infeasibility penalties are set high enough to discourage network violations except under extreme realizations.

Case study setup

The case study uses a realistic radial distribution feeder with high photovoltaic penetration, electric vehicles, residential and commercial flexible loads, battery storage, and inverter-based reactive support. Network-aware flexibility-request studies show that the feeder location of flexibility is crucial because identical flexibility quantities can have different congestion and voltage impacts depending on where they are activated [15]. Renewable scenarios are built from the forecast-error model, while prosumer response scenarios are generated from the compliance assumptions described earlier.

Benchmark models

The proposed model is compared with a deterministic benchmark and a risk-neutral stochastic benchmark. Deterministic clearing follows the expected forecast and expected compliance assumptions, while the risk-neutral model considers scenarios but minimizes average loss rather than tail exposure. Prior work on optimal flexibility procurement shows that benchmark comparisons are necessary because lower expected cost can conceal reliability degradation when uncertainty is ignored [8].

Computational performance

The model remains tractable because uncertainty is represented through a reduced scenario set and the feeder physics are incorporated through a linearized network approximation. Market-clearing approaches based on decomposition and distributed coordination show that flexibility problems can be scaled by exploiting separability across participants and scenarios [9]. In this implementation, the risk-aware model requires more computation than deterministic clearing, but it provides stronger protection against severe renewable, compliance, and network outcomes.

Results and Discussion

Cost, carbon, and reliability

The risk-aware model procures slightly more reliable flexibility and makes greater use of storage and high-compliance resources than the risk-neutral benchmark. Demand-response uncertainty studies explain this outcome because resources with low offer prices may become expensive in operational terms when non-compliance risk is considered [19]. The model also reduces carbon-intensive recourse by anticipating renewable underproduction and prioritizing flexibility that remains deliverable under adverse conditions.

Sensitivity to risk aversion and non-compliance

Sensitivity analysis shows that higher risk aversion shifts procurement away from low-cost but uncertain prosumer response and toward resources with stronger delivery reliability. Residential demand-management studies show that uncertain household response can reduce aggregate flexibility quality, especially when comfort, mobility, and rebound effects interact with market stress [20]. The following table compares the proposed risk-aware model with risk-neutral and deterministic clearing using qualitative performance categories rather than formula-based indicators.

Table 3. Comparative Performance of Deterministic, Risk-Neutral, and Risk-Aware Market-Clearing Models

Model	Expected operating cost	Tail-risk exposure	Carbon outcome	Flexibility shortfall	Network feasibility	Procurement pattern
Deterministic clearing	Lowest apparent cost	Highest exposure	Highest reliance on carbon recourse	Frequent underdelivery in adverse conditions	Most vulnerable to congestion and voltage stress	Favors cheapest offers and expected availability

Risk-neutral stochastic clearing	Moderate cost	Moderate exposure	Lower carbon recourse than deterministic clearing	Reduced average shortfall	Better feeder feasibility under common scenarios	Balances price and average reliability
Proposed risk-aware clearing	Highest planned procurement discipline	Lowest exposure	Lowest severe carbon outcome	Strongest protection against underdelivery	Strongest protection under adverse scenarios	Favors reliable, locationally useful, low-carbon flexibility

Conclusion

This article developed a risk-aware optimization model for low-carbon flexibility market clearing under renewable forecast errors, prosumer non-compliance, and distribution-network constraints. The model treats flexibility as an uncertain delivered service rather than a guaranteed contracted quantity, which makes it better aligned with real distribution-system operation.

The proposed approach shows how conditional value-at-risk can be used to limit severe outcomes associated with flexibility shortfalls, carbon-intensive recourse, and feeder-security stress. By combining renewable uncertainty, behavioral response uncertainty, and linearized network constraints, the model provides a practical decision-support tool for market operators.

The case study demonstrates that risk-aware clearing changes procurement patterns by favoring reliable and locationally valuable resources over cheaper but uncertain flexibility. This improves resilience against adverse renewable and prosumer realizations while preserving the low-carbon purpose of the market.

Future extensions should consider real-time re-clearing, multi-energy flexibility, dynamic network reconfiguration, and learning-based updates of compliance behavior. These developments would further improve the practical implementation of risk-aware flexibility markets in active distribution systems.

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