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A Theory-Building Model of Grid Flexibility Valuation under Prosumer Demand Response, DER Aggregation, and Local Congestion Management

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Abstract

The value of distribution-level flexibility is increasingly important as electricity systems become more decentralized, variable, and prosumer-oriented. Prosumers, aggregators, and network constraints jointly shape whether flexible capacity becomes technically useful and economically valuable. Existing research lacks a unified theory that explains how flexibility value emerges from the interplay of prosumer decision-making, DER aggregation, and local congestion management. As a result, valuation is often treated as either a market-pricing problem, a network-operations problem, or a behavioural-participation problem rather than as a co-determined process. This article builds a theory model linking prosumer demand response, DER aggregation, and local congestion management to the valuation of grid flexibility. The model explains how distributed flexibility becomes valuable when behavioural willingness, aggregation capability, and network scarcity align. The model is developed conceptually, drawing on microeconomics, mechanism design, contract theory, and grid operation principles. It is intended to generate causal explanations and testable propositions rather than empirical estimates or optimization results. The model identifies causal pathways from prosumer behaviour and aggregator strategies to flexibility value, moderated by congestion intensity. Seven propositions articulate testable relationships, while the full model distinguishes flexibility creation, coordination, scarcity revelation, and value allocation. The theory provides a foundation for future empirical testing and can inform market design and regulatory decisions for flexibility services. It clarifies why flexibility value cannot be attributed to DER assets alone but must be understood as an institutional and network-contingent outcome.

Keywords Distribution grid, Flexibility valuation, Prosumer demand response, DER aggregation, Congestion management, Theory-building

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Introduction

Distribution grids are increasingly expected to host electrified heating, electric vehicles, batteries, photovoltaic generation, and controllable loads, making flexibility valuation a central problem in electricity-market design. The value of flexibility is not merely the marginal saving from shifting load; it depends on when, where, and through whom the flexibility is activated, as shown by work on distribution-level flexibility markets [1]. This article argues that flexibility value is jointly produced by prosumers who supply behavioural and technical responsiveness, aggregators who transform dispersed resources into marketable portfolios, and distribution system operators who face local network constraints. A theory-

building approach is therefore needed because the relevant value is not inherent in a device but emerges through coordinated institutional arrangements.

The existing literature has advanced important elements of this problem, yet these elements often remain separated across research streams. Studies of prosumer demand response show how tariffs and incentives affect household flexibility provision [2], while local flexibility-market models explain how DSO requests can be matched with distributed resources [3]. Other contributions examine decentralized market design and the role of peer-to-peer or flexibility trading in coordinating distributed agents [4]. The theoretical gap is that these studies do not fully explain how prosumer willingness, aggregator strategy, and congestion scarcity co-determine the realized value of flexibility.

This article develops a conceptual model in which flexibility value is treated as a relational outcome rather than a fixed attribute of distributed energy resources. In this view, prosumer flexibility becomes economically meaningful only when an aggregator can bundle it into a reliable service and when the distribution network has a locational need for that service [5]. Mechanism-design perspectives suggest that the rules governing flexibility procurement can shape both efficiency and fairness [6]. The model therefore links micro-level behavioural decisions, meso-level aggregation mechanisms, and system-level congestion conditions into a single theoretical account.

The contribution is threefold. First, the article reframes grid flexibility valuation as a problem of multi-actor value co-determination rather than isolated asset valuation, extending the logic of local flexibility-market frameworks [7]. Second, it explains why the same physical flexibility may have different values across locations, time periods, and market designs, consistent with hierarchical coordination approaches to local energy and flexibility trading [8]. Third, it generates propositions that can guide future empirical and simulation-based testing without reducing the theory to an optimization model. The aim is analytical: to clarify causal mechanisms through which distributed flexibility is created, bundled, priced, and allocated under congestion.

Theoretical Problem

The valuation gap

The core valuation gap is that distribution-level flexibility is often priced as though it were a homogeneous commodity, even though its usefulness depends on reliability, location, timing, rebound effects, and network state. Regional flexibility-market studies show that products differ in activation time, duration, direction, and locational specificity [9], which means that valuation must account for service attributes rather than only energy quantity. A kilowatt of load reduction behind a congested transformer may have a higher value than the same kilowatt elsewhere because it relieves a specific constraint. The model therefore starts from the premise that flexibility value is conditional, situated, and institutionally mediated.

Multi-actor value co-determination

Flexibility value is co-determined because no single actor independently produces it. Prosumers supply controllable potential, aggregators make that potential visible and tradable, and DSOs define the operational scarcity that creates demand for congestion-relief services, a logic reflected in characterizations of flexibility across power systems and markets [10]. This co-determination implies that valuation cannot be inferred from device capability alone. It must instead be theorized as the outcome of interaction among preferences, contracts, market rules, and network constraints.

Research question

The guiding research question is: how is the value of grid flexibility theoretically produced through the interaction of prosumer demand response, DER aggregation, and local congestion management? Stochastic local flexibility-market designs indicate that bidding, dispatch, and network operation are interdependent [11], but a theory-building article must

explain the underlying causal mechanisms rather than solve for an optimal dispatch. The model asks when flexibility becomes valuable, who can capture that value, and how congestion intensity changes the distribution of benefits. It thereby connects economic valuation, institutional coordination, and operational scarcity in a single explanatory framework.

Prosumer Flexibility Background

Prosumer types and motivations

Prosumers differ in technology portfolios, preferences, risk tolerance, comfort expectations, environmental motives, and willingness to delegate control. Residential demand response research shows that participation depends on motivators such as financial compensation, perceived convenience, automation, and trust in the controlling party [12]. A household with solar photovoltaics and a battery may view flexibility as an opportunity for revenue, whereas a household with heat pumps or thermostatically controlled loads may treat flexibility as a comfort trade-off. The model therefore treats prosumer flexibility supply as preference-conditioned rather than purely technical.

Demand response models

Demand response models translate prosumer willingness into temporal adjustments in consumption, generation, or storage operation. Distribution-tariff research demonstrates that tariff design can shape prosumer responsiveness and self-consumption incentives [2], which implies that flexibility supply depends on price signals as well as household constraints. In theoretical terms, a prosumer supplies flexibility when the expected compensation or indirect benefit exceeds perceived inconvenience, risk, and loss of autonomy. This creates a behavioural supply curve that may be discontinuous, context-dependent, and sensitive to contract framing.

Flexibility supply characteristics

The supply of prosumer flexibility has attributes that determine whether it can be valuable in grid operations. Trading models for small prosumers show that flexibility can be offered into energy and reserve markets when it is sufficiently measurable, dispatchable, and aggregable [13]. However, flexibility from households is often uncertain because it depends on occupancy, appliance availability, weather conditions, and competing user priorities. The model therefore distinguishes latent flexibility, which exists physically, from committed flexibility, which has been contractually or behaviourally made available for activation.

Uncertainty and behavioural factors

Uncertainty is central because prosumers may fail to respond, override control signals, or change preferences over time. Evidence from local flexibility-market participation suggests that trust, perceived fairness, administrative burden, and social acceptance influence whether consumers engage with flexibility arrangements [14]. These behavioural factors affect not only the quantity of flexibility supplied but also its reliability and therefore its valuation. The model proposes that behavioural uncertainty creates a discount on flexibility value unless aggregators or market rules can reduce it through automation, guarantees, or incentive-compatible contracts.

Flexibility Valuation Concepts

Economic fundamentals of flexibility value

Flexibility value arises when a resource can alter the timing, location, or magnitude of electricity consumption or production in a way that reduces system costs or prevents constraint violations. Market-design work on decentralized distribution flexibility indicates that prices must reveal local scarcity while giving agents incentives to act efficiently [4].

From a microeconomic perspective, flexibility has derived demand because its value depends on the avoided cost of an alternative action, such as reinforcement, curtailment, redispatch, or reliability degradation. Thus, flexibility valuation must be linked to the problem it solves rather than to the device that provides it.

Real options and avoided costs

Flexibility also has option value because it preserves the ability to defer irreversible investments under uncertainty. Reviews of TSO-DSO-customer flexibility trading show that distributed flexibility can act as an alternative to network expansion or centralized balancing when procurement and coordination are well designed [15]. The value of this option increases when demand growth, DER adoption, and congestion patterns are uncertain. The model therefore conceptualizes flexibility as both an operational service and a strategic hedge against premature infrastructure commitments.

Market-based vs. regulated valuation

Market-based valuation uses bids, clearing mechanisms, and competition to reveal willingness to supply and willingness to pay for flexibility, whereas regulated valuation relies on administratively defined compensation or cost-recovery rules. Mechanism-design studies of DSO flexibility markets emphasize that rules must balance efficiency, truthfulness, and fairness [6]. A purely market-based system may better reveal scarcity but can also expose DSOs or prosumers to strategic behaviour, while regulated compensation may be more stable but less responsive to local conditions. The proposed theory treats valuation as a governance choice that shapes who participates, how scarcity is signalled, and how rents are distributed.

Time and locational granularity

The value of flexibility increases with the precision of time and location when congestion is localized and temporally concentrated. Network-aware flexibility requests demonstrate that distribution-level procurement must reflect physical constraints rather than rely only on system-wide price signals [16]. Similarly, dynamic operating-envelope approaches show that export and import limits can vary across customers and time, making granular allocation central to efficient operation [17]. The model therefore argues that valuation becomes more accurate as flexibility products move from generic energy shifts toward locationally and temporally specified services.

DER Aggregation Mechanisms

Aggregator roles and business models

Aggregators mediate between dispersed prosumers and flexibility buyers by recruiting participants, forecasting availability, controlling resources, managing risk, and submitting market offers. Business-model research on demand response emphasizes that flexibility creation depends on value propositions, customer relationships, revenue streams, and operational capabilities [18]. Aggregators therefore do not simply collect existing flexibility; they actively construct tradable services from heterogeneous and uncertain resources. In the theory model, the aggregator is a value-transforming intermediary that converts latent prosumer responsiveness into credible network services.

Bundling heterogeneous resources

Bundling is the mechanism through which small, variable, and heterogeneous DERs become large and reliable enough to meet flexibility-market requirements. Aggregator strategy research shows that firms must avoid being “too small to bid” by combining resources and designing portfolios that satisfy minimum bid sizes and reliability expectations [19]. Heterogeneity can create portfolio benefits because batteries, electric vehicles, heat pumps, and thermostatically controlled loads have different response speeds, rebound risks, and availability patterns. The model proposes that

aggregation increases flexibility value when diversification reduces delivery uncertainty more than coordination costs increase.

Information asymmetry and market power

Aggregation also introduces information asymmetry because aggregators may know more than DSOs about resource availability, prosumer preferences, and portfolio reliability. Peer-to-peer and flexibility-market frameworks show that intermediated trading requires institutional rules that govern information exchange, settlement, and verification [7]. If aggregators can strategically withhold flexibility or inflate scarcity claims, the market price may diverge from the true operational value of congestion relief. The theory therefore treats aggregator market power as a possible distortion in value capture, especially where local congestion creates few substitutes.

Contract design and incentive compatibility

Contract design determines whether prosumers reveal flexibility honestly and whether aggregators can rely on promised responses. Reviews of mechanism design in demand-side management show that incentive compatibility, participation constraints, and allocation rules are central to eliciting flexible behaviour without excessive information requirements [20]. A contract that overpays for availability may attract participation but weaken activation reliability, while a contract that over-penalizes non-delivery may discourage risk-averse prosumers. The model therefore argues that the value of aggregated flexibility depends on contracts that align prosumer welfare, aggregator profitability, and DSO operational needs.

Figure 1 illustrates how latent prosumer flexibility is converted into committed, aggregated, and locationally useful flexibility through contracts, portfolio formation, and congestion-aware procurement.

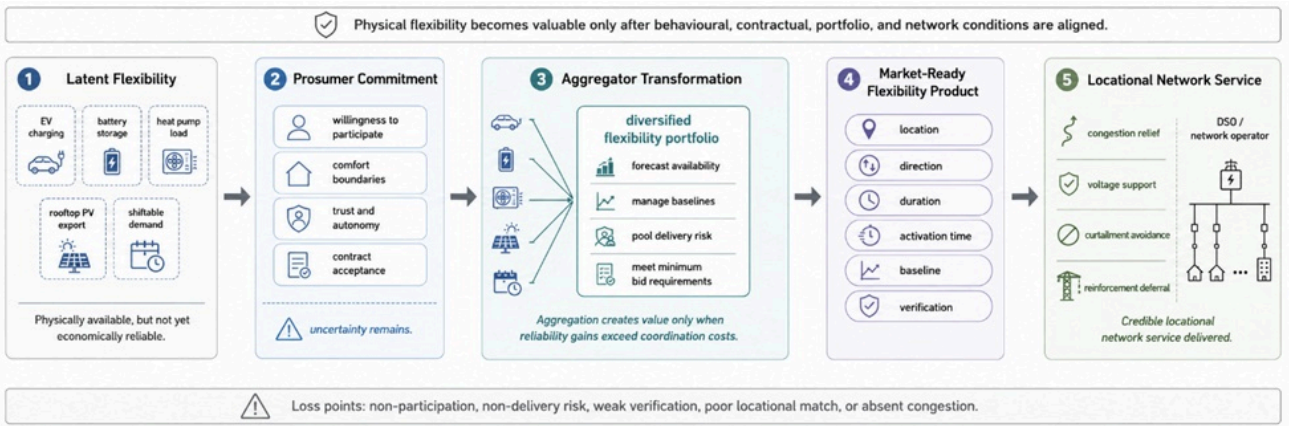


Figure 1. Flexibility Value Formation Pathway from Latent Prosumer Capacity to Locational Network Service

Congestion Management Mechanisms

Distribution network constraints

Distribution network constraints create the scarcity conditions under which flexibility becomes valuable. Congestion management-market design studies show that DSOs require flexible resources not because flexibility is generically desirable, but because particular lines, substations, feeders, or voltage conditions face operational limits at specific times [21]. The model proposes that congestion transforms prosumer flexibility from a private capability into a network-relevant service. Without a binding or expected constraint, the economic value of local flexibility is limited because the system has no urgent need for locational adjustment.

Congestion pricing and dynamic operating envelopes

Congestion pricing and dynamic operating envelopes represent two distinct but related ways of translating network constraints into economic or operational signals. Local flexibility-market design research argues that congestion-management products must be tailored to local needs, activation timing, and procurement responsibilities [22]. Dynamic operating-envelope studies further show that flexible import and export limits can allocate network capacity more adaptively than static connection rules [17]. The theory model treats these mechanisms as scarcity-revelation devices that convert hidden network constraints into actionable signals for aggregators and prosumers.

Locational value of flexibility

The locational value of flexibility depends on whether an action changes power flows at the constrained point in the network. Reviews of distribution-level flexibility markets emphasize that flexibility products must specify location, direction, duration, baseline, and verification arrangements to be useful for congestion management [23]. A flexible load outside the congested area may have little value for a local constraint, while a smaller response behind the constraint may avoid curtailment or reinforcement. The model therefore argues that locational effectiveness is a primary determinant of flexibility value and not merely an adjustment to a uniform market price.

Interaction with transmission-level markets

Distribution-level flexibility can interact with transmission-level balancing, reserve, and wholesale markets, creating both value-stacking opportunities and coordination risks. TSO-DSO coordination reviews show that flexibility may serve multiple buyers, but conflicting activations can worsen congestion or undermine local reliability if hierarchy and information exchange are poorly designed [24]. Market frameworks that link local energy and flexibility trading also indicate that coordination across levels is necessary to prevent double counting and incompatible dispatch [8]. The theory model therefore treats multi-level coordination as a boundary condition for realizing flexibility value without shifting costs across system layers.

Proposed Theory Model

Core constructs and definitions

The proposed model contains four core constructs: prosumer flexibility supply, aggregator bundling capability, congestion intensity, and realized flexibility value. Prosumer flexibility supply refers to the willingness and ability of households, communities, or small firms to modify consumption, generation, or storage, while aggregator bundling capability refers to the capacity to combine dispersed resources into a reliable service, as illustrated in renewable energy community and nanogrid flexibility frameworks [25]. Congestion intensity captures the degree to which local network constraints make flexibility scarce and operationally valuable. Realized flexibility value is the economic and institutional outcome produced when these constructs align under credible procurement and settlement rules.

Causal pathways

The model proposes that prosumer flexibility supply affects value first by determining the quantity, reliability, and comfort cost of available response. Aggregator bundling capability then mediates this effect by transforming uncertain individual responses into predictable portfolios, a role emphasized in technical virtual power plant frameworks for exploiting DER flexibility [26]. Congestion intensity moderates the pathway because the same aggregated portfolio has greater value when it relieves a binding or expected distribution constraint. Realized value therefore emerges through a causal chain from behavioural availability to portfolio credibility to network scarcity resolution.

Figure 2 presents the proposed theory model showing how prosumer flexibility supply, aggregator bundling capability, congestion intensity, and institutional coordination jointly determine realized grid flexibility value.

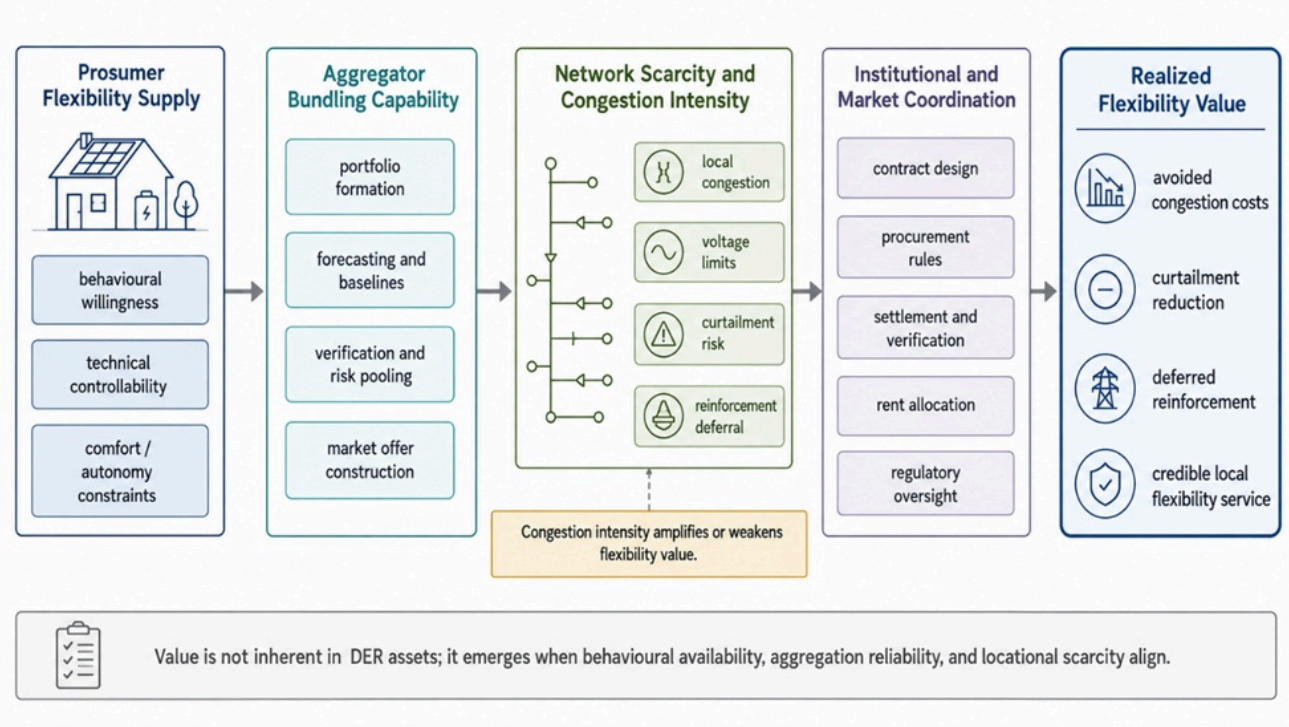


Figure 2. Multi-Actor Theory Model of Grid Flexibility Value Co-Determination

Moderating role of congestion

Congestion intensity is the main moderator because it changes both the demand for flexibility and the distribution of rents among actors. Flexibility-management models for home appliances show that controllable loads can support DSO requests, but their economic significance depends on whether such requests correspond to operational needs [27]. Under low congestion, prosumer flexibility may be valuable mainly for wholesale arbitrage or balancing, whereas under high local congestion it may become a scarce non-wire alternative. The model therefore predicts that congestion amplifies the marginal value of reliable, locationally effective, and quickly activatable flexibility.

Model boundary conditions

The model applies most strongly to distribution systems with meaningful DER penetration, observable local constraints, identifiable flexibility buyers, and market or regulatory arrangements that permit distributed participation. Flexibility-characterization research emphasizes that aggregation and market design become especially important as renewable penetration increases and system operation requires more granular coordination [28]. The model is less applicable where DSOs cannot procure flexibility, where metering and verification are weak, or where prosumer participation is legally or socially constrained. Table 1 summarizes the theory model's constructs, causal relationships, and mechanisms linking flexibility sources to value outcomes under congestion.

Table 1. Theoretical model of flexibility value creation under network congestion: constructs, mechanisms, and expected outcomes

Model component	Core construct	Primary actor	Mechanism linking flexibility to value	Expected value outcome under congestion

Behavioural availability	Prosumer flexibility supply	Prosumer	Willingness to shift, curtail, store, or export in response to compensation, automation, comfort limits, and trust	Higher value when willingness is reliable, controllable, and aligned with the timing of a local constraint
Portfolio formation	Aggregator bundling capability	Aggregator	Diversification of heterogeneous DERs, forecasting, baseline management, verification, and risk pooling	Higher value when aggregation reduces delivery uncertainty and creates a tradable service that meets DSO product requirements
Scarcity revelation	Congestion intensity	DSO and market operator	Prices, flexibility requests, dynamic limits, and procurement signals reveal where and when network capacity is scarce	Higher value when congestion is local, recurrent, costly to relieve through reinforcement, and responsive to flexible action
Institutional coordination	Market and contract design	Regulator, DSO, aggregator, prosumer	Rules allocate rights, obligations, information, penalties, and payments across actors	Higher value realization when incentives are compatible and rents are distributed without discouraging participation
Value realization	Realized flexibility value	Multi-actor system	Alignment of prosumer response, aggregator reliability, and congestion-relief effectiveness	Flexibility becomes valuable when it avoids curtailment, defers reinforcement, improves reliability, or reduces redispatch costs

Propositions

Prosumer flexibility supply and value

Proposition 1: The realized value of grid flexibility increases when prosumer flexibility supply is both behaviourally acceptable and technically controllable. Residential preference research suggests that participation in direct load control depends on compensation, perceived inconvenience, trust, and control arrangements [12], so the model expects low participation to reduce the value of even technically capable DERs. Proposition 2: Flexibility value is discounted when prosumer response is uncertain, comfort-sensitive, or difficult to verify. Under these conditions, the market prices not only energy adjustment but also the risk that promised flexibility will not materialize.

Aggregator bundling and value capture

Proposition 3: Aggregator bundling increases realized flexibility value when portfolio diversification reduces uncertainty more than it increases coordination and transaction costs. Aggregator business-strategy research indicates that minimum bid sizes, customer recruitment, and service design shape whether small resources can become market-relevant [19]. Proposition 4: Aggregators capture a larger share of flexibility value when they control scarce information about availability, baselines, and delivery risk. This value capture may support market formation, but it may also create rents if local competition is weak or DSO procurement depends on a small number of intermediaries.

Congestion intensity and value distribution

Proposition 5: Congestion intensity positively moderates the relationship between aggregated flexibility reliability and realized value. Local flexibility-market taxonomies show that congestion-management design depends on product definition, procurement timing, network representation, and settlement rules [29], which means scarcity must be institutionally translated before it becomes a price or payment. Proposition 6: As congestion becomes more localized and

recurrent, flexibility value shifts from generic energy-market value toward locational network value. Under such conditions, prosumers and aggregators located behind the relevant constraint are expected to gain stronger bargaining positions.

Interaction effects

Proposition 7: The highest realized flexibility value occurs when high prosumer willingness, strong aggregator bundling capability, and high congestion intensity coincide. ADMM-based market-clearing research illustrates that flexibility bidding and congestion management are interdependent even when treated computationally [30], while the present theory explains why that interdependence arises institutionally. If any element is missing, value creation weakens: prosumer willingness without aggregation remains fragmented, aggregation without congestion has limited network value, and congestion without reliable flexible response leads back to reinforcement or curtailment. The model therefore predicts complementarity among behavioural, organizational, and network mechanisms.

Figure 3 maps the seven theoretical propositions across behavioural supply, aggregator bundling, congestion intensity, value capture, and interaction effects.

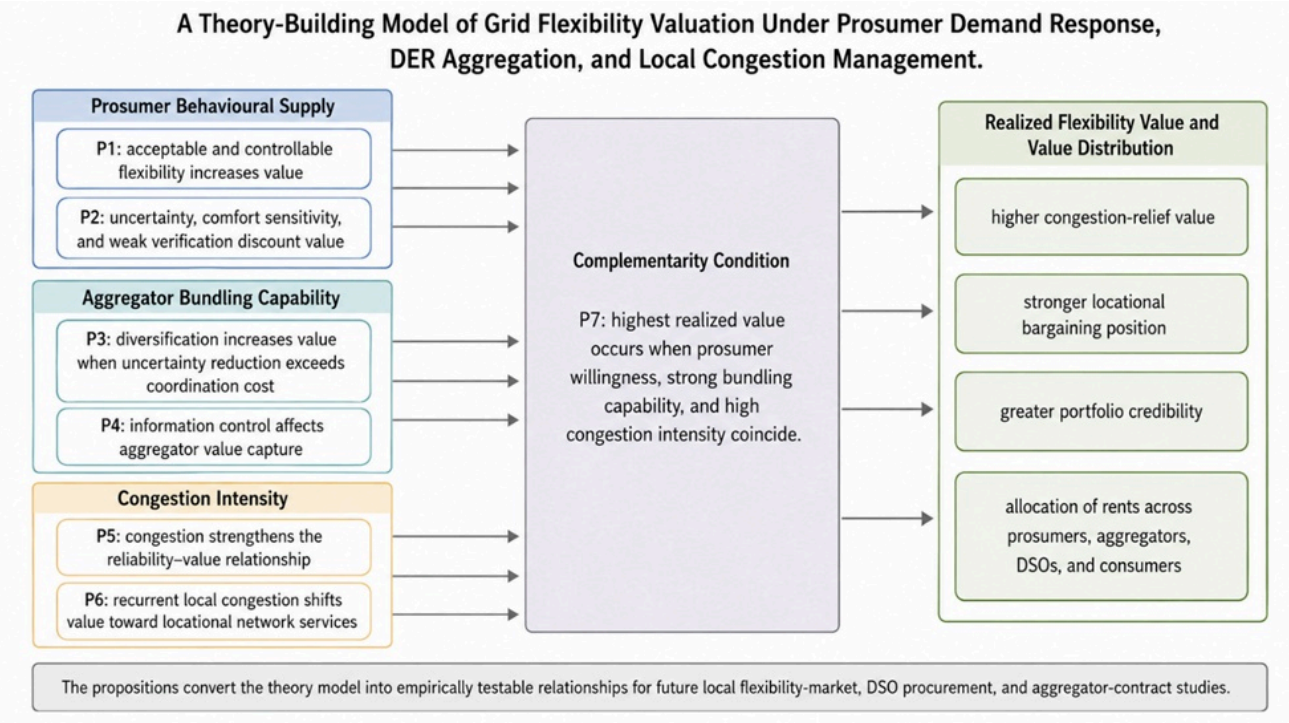


Figure 3. Proposition Map Linking Behavioural, Aggregation, and Congestion Mechanisms to Flexibility Value Outcomes

Implications

Implications for flexibility market design

The model implies that flexibility markets should be designed around service attributes rather than undifferentiated kilowatt quantities. Physical storage-rights research shows that market mechanisms can allocate flexibility-like rights in ways that link physical constraints to economic commitments [31], supporting the broader claim that market products must reflect network realities. Designers should therefore specify location, direction, duration, verification, baseline, and activation priority so that flexibility prices correspond to actual congestion-relief value. The theory also implies that market rules should limit information rents while preserving aggregator incentives to recruit and coordinate prosumers.

Implications for DSO regulation

For DSO regulation, the model suggests that flexibility procurement should be evaluated as a governance problem rather than only as a least-cost technical option. Congestion-management design for Nordic and Central European settings shows that institutional context shapes whether local markets, bilateral procurement, or regulated mechanisms are appropriate [21]. Regulators should therefore ask whether DSOs have incentives to compare flexibility with reinforcement, whether aggregators can participate without excessive barriers, and whether prosumers receive credible compensation for availability and activation. The model further implies that dynamic operating envelopes and local markets should be coordinated so that operational limits, price signals, and contractual obligations reinforce rather than contradict one another.

Conclusion

This article has developed a theory-building model of grid flexibility valuation under prosumer demand response, DER aggregation, and local congestion management. The central claim is that flexibility value is not an intrinsic property of distributed energy resources. Instead, it emerges when prosumer willingness, aggregator coordination, and local network scarcity are brought into alignment. The theory therefore reframes flexibility valuation as a multi-actor process of value creation, transformation, revelation, and allocation.

The model identifies three principal causal mechanisms. First, prosumer behaviour determines whether latent technical flexibility becomes available as a socially and contractually acceptable response. Second, aggregation transforms uncertain individual responses into a portfolio that can be forecast, verified, and traded. Third, congestion creates the operational scarcity that determines whether the portfolio has high local network value.

The propositions specify expected relationships among these mechanisms. Prosumer flexibility is expected to have greater value when it is reliable, controllable, and acceptable to participants. Aggregator bundling is expected to increase value when it reduces uncertainty and meets market-product requirements. Congestion intensity is expected to amplify locational value and shift bargaining power toward actors capable of relieving specific constraints.

Future research can test the model empirically by examining local flexibility markets, DSO procurement schemes, aggregator contracts, and prosumer participation behaviour across different regulatory settings. Comparative studies could assess when value is captured by prosumers, aggregators, DSOs, or consumers more broadly. The theory also invites institutional analysis of how market rules, dynamic operating limits, and contract structures influence the fairness and efficiency of flexibility valuation. In this sense, the article provides a conceptual foundation for future research and policy design in increasingly decentralized electricity systems.

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