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Review

A Scoping Review of Flexibility Markets in the Power Sector: Models, Mechanisms, and Business Perspectives

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Abstract

The transition to decarbonized and distributed energy systems has increased interest in flexibility markets as a key tool to manage variability and coordinate distributed energy resources. However, the fast growth and conceptual fragmentation of this field hinder the building of coherent models and scalable solutions. This paper presents a scoping review of 243 peer-reviewed articles published between 2013 and 2025, applying the TEAM Framework and Business Model Canvas. Through a structured data matrix of 35 variables, we analyze how flexibility is defined and modelled, the coordination mechanisms applied, and how business dimensions are integrated. The results reveal major inconsistencies in terminology, actor roles, price formation, and interoperability modelling. We identify critical gaps in cost modelling and business model integration, especially in low-TRL studies. This review provides a comprehensive and cross-cutting synthesis of existing approaches, offering a reference framework for future research, policy design, and market implementation of distributed flexibility mechanisms.

Keywords: aggregators; business model canvas; demand response; distributed energy resources; flexibility markets; market design; TEAM framework

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1. Introduction

Global energy systems are undergoing a profound transformation, driven by decarbonization targets, electrification of end-uses, and the growing penetration of variable renewable energy sources. For system operators (SOs), this transition brings major challenges in balancing supply and demand under increasing uncertainty and spatial–temporal variability. Conventional infrastructure-based solutions, such as grid reinforcement, are often costly, slow to implement, and insufficient for addressing temporary operational needs. As a result, future power systems will increasingly depend on enhancing their operational flexibility [1].

In this context, flexibility markets have emerged as promising instruments to unlock demand-side responsiveness, leverage distributed energy resources (DERs), and enable storage capabilities. These markets aim to optimize asset utilization and defer costly investments by procuring services—such as load shifting, congestion management, and frequency regulation—through market-based mechanisms. Initially developed at the local level, flexibility markets are gaining strategic importance as regulatory programmes in many countries promote their standardization, scalability, and integration into existing electricity markets [2].

Despite their growing relevance, flexibility markets remain a fragmented and evolving field. The definition, measurement, and operationalization of flexibility vary considerably across studies, depending on disciplinary perspectives—technical, economic, regulatory, or institutional. Similarly, actor roles and coordination schemes differ widely, encompassing centralized, distributed, and hybrid models involving aggregators, DSOs, TSOs, and prosumers. This heterogeneity across studies limits the transferability of results to other settings or scales.

Given the rapid expansion of the literature and the lack of conceptual alignment, a comprehensive and structured review is needed to synthesize existing knowledge on flexibility markets. Prior reviews have typically focused on specific technologies, case studies, or regulatory frameworks. Few provide a cross-cutting comparison that systematic addresses market designs, actor roles, coordination models, and business perspectives. Without such synthesis, policymakers, researchers, and practitioners may struggle to identify the best practices, knowledge gaps, and scalable solutions for diverse energy system contexts.

Several existing reviews have explored flexibility in distribution networks [1,3], local market designs [4–7], and demand response business models [8,9]. However, none offer a systematic analysis that integrates technical architectures, coordination paradigms, and value creation mechanisms within a unified analytical framework.

To address this gap, we adopt the following two complementary approaches: Business Model Canvas and the TEAM Framework. Together, they capture both the structural coordination of actors and the mechanisms through which flexibility creates value. This review analyzes 243 peer-reviewed articles published between 2013 and January 2025, focusing on how flexibility is conceptualized, modelled, and implemented across various contexts. The proposed methodology offers a rigorous foundation for future research and policy development by identifying key patterns, conceptual inconsistencies, and underexplored areas. It aims to support on the design and implementation of technically sound, economically viable, and socially inclusive flexibility markets.

2. Materials and Methods

This study follows the PRISMA-ScR guidelines (see Supplementary Materials) to ensure transparency, reproducibility, and systematic rigour. The analytical approach combines two complementary frameworks—TEAM and the Business Model Canvas—to enable a multidimensional analysis of flexibility markets. All data extraction procedures, eligibility criteria, and data synthesis methodologies are detailed below. The data sources, code architecture, and extraction matrix used in the study are available at https://doi.org/10.5281/zenodo.15572885.

2.1. Protocol and Registration

This scoping review was conducted following the PRISMA-ScR guidelines. No review protocol was registered or published in advance. As this is common in scoping reviews that explore emerging and interdisciplinary research areas, the absence of a protocol does not jeopardize methodological transparency.

2.2. Eligibility Criteria

To guarantee both relevance and consistency in the review, the following set of inclusion criteria was established:

- **Type of publication**: Eligible documents included peer-reviewed journal articles and conference papers.

- **Source quality and accessibility**: Grey literature, technical reports, and non-peer-reviewed sources were excluded. Only articles with full-text access and a valid DOI were included.
- **Thematic scope**: Studies concentrated on energy flexibility marketplaces, flexibility methods, coordinating techniques, enabling technology, and business models.
- **Language**: Only studies published in English were considered.

2.3. Information Sources and Search Strategy

The bibliographic search was conducted in January 2025 across the following three primary scientific databases and yielded 1363 initial records:

- In **Web of Science** (WoS), we employed the terms "*Flexibility Markets*" and "*Peer to Peer review*", resulting in 319 records.
- In **Scopus**, we applied the query "*TITLE-ABS (flexibility AND markets AND energy) AND KEY (flexibility AND market)*", limited to journals and conferences, which yielded 543 results.
- In **IEEE Xplore**, we used as search parameters "*("Document Title": Flexibility markets) OR ("Publication Title": Flexibility market) OR ("Author Keywords": Flexibility market)*", and restricted to journals and conference proceedings, retrieving 501 documents.

2.4. Selection Process

The following two-step process was applied to reduce the initial set of 1363 articles to 243 eligible studies: identification and screening.

- **Identification:** Duplicate records were removed based on DOI and title matching, reducing the dataset to 1302 articles.
- **Screening:** This stage involved two steps. First, a language filter was applied and titles were screened to retain only English-language publications and exclude clearly unrelated topics, resulting in 743 articles. Second, records containing irrelevant keywords or whose abstracts were misaligned with the research scope were excluded, yielding a final set of 243 articles.

The full selection process is illustrated in Figure 1.

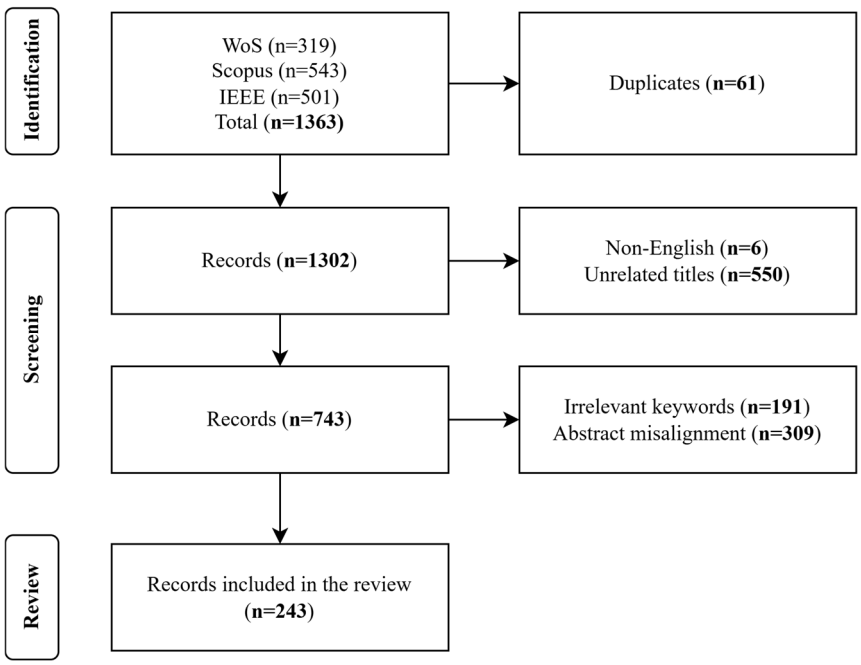


Figure 1. Selection process.

2.5. Data Charting Process

To capture relevant information from each article, we developed a structured data extraction matrix organized around the following three guiding components:

- **PRISMA-ScR** principles to ensure replicability and methodological transparency.
- **TEAM Framework (Technology–Economy–Actor–Market)** to examine actor interactions, coordination models, and systemic architectures in flexibility markets. This framework integrates concepts such as Moore's metaphor, coordination theory, and value modelling, allowing analysis across technical, economic, and institutional dimensions according to the Business Ecosystem Architecture Modelling [10]. For instance, it captures whether coordination is centralized or distributed, what level of market integration is pursued, and how actors relate within the system. Ref. [11] illustrates a comparable application to peer-to-peer energy markets, which, although governed differently, share key functional traits with flexibility markets (e.g., decentralized control and value exchange).
- **Business Model Canvas** to identify economic mechanisms and organizational aspects of flexibility markets. This includes value propositions, customer segments, revenue structures, and cost models. While prior reviews [3,12–14] have applied simplified or case-specific versions of the BMC, our approach uses a comprehensive and comparative structure across all included articles.

Our data matrix incorporates 35 variables, grouped into seven thematic areas (see Appendix A Table A1), including definitions, algorithms, actors, tariffs, and business dimensions. The matrix was tested with a pilot subset of 20 articles and refined iteratively. Data extraction was conducted manually by the research team, and each entry was independently reviewed for accuracy and consistency.

2.6. Critical Appraisal and Synthesis of Results

No critical assessment was conducted. Instead, a relevance rating was used to assess the contribution of each study.

3. Results

This section presents the main findings of the systematic review based on structured analysis of the 243 selected articles. The results are organized into six areas corresponding to the categories defined in the data extraction matrix. Each subsection provides a concise summary of the evidence, its interpretation in relation to the research objectives, and relevant insights. Section 3.1 offers an overview of the general characteristics of the included studies. Section 3.2 explores how flexibility is conceptualized and defined. Section 3.3 discusses key modelling assumptions and interoperability aspects. Section 3.4 focuses on market participants and enabling actors. Section 3.5 analyses coordination mechanisms and transactional elements, in line with the TEAM framework. Finally, Section 3.6 examines the integration of business model components.

3.1. Overview of Included Studies

The final dataset comprises 243 peer-reviewed articles published between 2013 and 2025, showing a clear growth in academic interest in flexibility markets. Most contributions appeared in the last five years. Modelling studies dominate the sample, followed by empirical and review articles, highlighting the quantitative focus of current research. Experimental studies remain scarce, reflecting the early deployment stages of many flexibility solutions. The reviewed papers span a wide range of journals and conferences, confirming the interdisciplinary nature of the field, which connects energy systems, smart grids, market design, and policy.

3.2. Flexibility Conceptualization

3.2.1. Definition

The literature approaches flexibility from diverse perspectives, reflecting the variety of disciplinary backgrounds and actor roles involved. Some authors define flexibility as "*the ability to modify generation or consumption in response to external signals*"—typically price incentives or grid constraints—emphasizing operational and economic aspects [12,13]. Others adopt a broader system-level view, framing flexibility as a key enabler of system stability and resilience, especially in the context of renewable integration and uncertainty management [14,15]. These conceptual differences are not merely semantic: they influence how flexibility is modelled, what metrics are used, and which actors participate. Techno-economic studies often treat flexibility as a tradable resource, quantifiable by parameters such as power capacity, activation cost, and response time. In contrast, policy and institutional analyses focus on flexibility as a strategic function within multi-actor governance frameworks, emphasizing access, roles, and coordination [16].

From a quantitative perspective, flexibility is often characterized as the variation capacity of a resource over time, under constraints. A generic expression to capture flexibility (F) could be the following:

$$F(t) = \frac{dP(t)}{dt}, \quad P_{min} \leq P(t) \leq P_{max}, \tag{1}$$

where $P(t)$ is the power at time t, and $\frac{dP(t)}{dt}$ represents the rate of change. This expression reflects the resource's ability to increase or decrease its output in response to system needs or price signals. Many studies expand this model by incorporating cost functions, time windows, and probabilistic constraints.

From a theoretical perspective, some studies offer precise, often system-specific formal definitions for flexibility such as "possibility of modifying generation and/or consumption patterns in reaction to an external signal (price or activation signals) to contribute to the power system stability in a cost-effective manner" [4], while others rely on implicit assumptions where flexibility is not defined but modelled through response functions, agent behaviours, or optimization routines [17]. This lack of standardization hampers comparison between models and limits result transferability. It also reinforces the need for clear, actor-sensitive definitions, particularly as flexibility evolves from a technical concept into a structured market service [18].

Based on our systematic analysis, we propose the following definition from a functional and cross-cutting perspective:

Definition 1: *"Flexibility is the ability of demand, generation, and storage to adapt under conditions of variability and uncertainty, in order to provide grid services in line with technical constraints or price signals".*

This definition aims to support interoperability between disciplines, enable consistent comparison across studies, and encourage shared understanding in the design and operation of flexibility markets.

3.2.2. Metrics

The reviewed literature reveals a wide range of metrics to evaluate flexibility, reflecting diverse objectives and disciplinary approaches. These metrics can be grouped into the following seven categories (Table 1), each addressing a specific dimension of flexibility value:

- **Capacity and power availability**: Quantifies the amount of flexible energy or power that can be traded. Common indicators include ramp-up/down rates, dispatchability, curtailed energy, and load shift volume. This is the most widely used category, especially in capacity planning and operational scheduling.
- **Temporal responsiveness**: Captures how quickly and accurately a resource reacts to control signals, using metrics like response time, ramp rate, delay, and activation window. This is the second prominent group, especially in short-term operations.
- **Cost–benefit metrics**: Relate flexibility provision to economic performance, using activation cost, market revenues, and profit margins. These metrics are central to techno-economic evaluations and business model assessments.
- **Reliability and variability**: Assess the likelihood that flexibility will be available when needed. Probabilistic indicators such as Lack of Ramp Probability (LORP) and Insufficient Ramping Resource Expectation (IRRE) are used under high shares of renewables.
- **Market and clearing performance**: Evaluate how flexibility affects system efficiency and price signals. Key indicators include Market Clearing Price (MCP), activation ratio, and convergence time. This category features prominently in market design and simulation studies.
- **Capacity adequacy under uncertainty**: Focuses on system robustness to operate securely under uncertainty. Metrics like System Capability Ramp (SCR) and Ramping Capability Shortage Expectations (RCSE) are used in stress-test scenarios and long-term planning, though only a few studies apply them.
- **Technical and grid-level indicators**: This category connects flexibility to grid performance and includes voltage deviations and RES hosting capacity. These are essential for distribution system operators (DSOs) and grid reinforcement planning.

Table 1. Metrics.

Category	Metrics	References
Capacity and power availabilityt	Flexibility Ramp-Up	[4,17,19]
	Flexibility Ramp-Down	[4,17,19]
	Load shift volume	[1,20]
	Curtailed energy	[21]
	Energy capacity	[22]
	Dispatchability	[4,17]
	Power	[2,23–41]
Temporal responsiveness	Response Time	[6,20,22,28,31,42–53]
	Ramp Rate	[15,42,50,54–57]
	Delay	[8,14,18,58–60]
	Start-up Time	[17]
	Activation Window	[17]
Cost–benefit metrics	Activation cost	[21,42,48,50,51,61,62]
	Market revenue	[9,63,64]
	Profit margin	[3,21,63,65]
Reliability and variability	IRRE	[4,19]
	LORP	[4,19]
Market and Clearing Performance	MCP	[66]
	Activation ratio	[5,67]
	Social welfare	[19,34,68–78]
	Efficiency	[5,20,24,28,51,57,66,73,79–91]
	Convergence time	[92,93]
Capacity adequacy under uncertainty	SCR	[17,94]
	RCSE	[17]
Technical and grid-level indicators	Voltage deviation	[37,38,95–97]
	Hosting capacity	[78,97,98]

Overall, capacity and cost-based indicators dominate the literature, especially in centralized and techno-economic studies. However, these tend to underrepresent grid-level effects, responsiveness, and uncertainty management. While indicators related to market performance are gaining traction, social and participatory dimensions remain largely unaddressed.

3.3. Modelling Assumptions and Interoperability

3.3.1. Rationality

In flexibility market modelling, *rationality* refers how agents—such as consumers, producers, system operators, and aggregators—make decisions in response to prices, incentives, information, and constraints. This is a key modelling factor, as it influences how behaviour is simulated and how market outcomes are interpreted. The literature identifies the following three main rationality assumptions:

- **Perfect rationality or symmetry**: Agents have full information, unlimited computational capacity, and act to maximize utility or profit.
- **Bounded rationality**: Agents operate under limited information or cognitive constraints, often following heuristics or behavioural rules.
- **Unspecified**: The model does not explicitly state how agent decisions are determined.

Our analysis reveals that 65.8% of studies assume bounded rationality, especially those using agent-based models, heuristics, or simulations involving prosumers, local markets, and distributed coordination schemes. In total, 14.4% of studies apply perfect rationality, typically in theoretical or centralized models involving TSO–DSO coordination or system-wide optimization. The remaining 19.8% do not specify rationality assumptions, often in conceptual, architectural, and regulatory analyses. The predominance of bounded rationality aligns with the increasing complexity of flexibility markets and highlights the trend toward more realistic, distributed, and computationally tractable modelling approaches.

3.3.2. Perfect Information

Information availability is key in energy market modelling. It determines how agents perceive system conditions, prices, and the actions of others. This is typical in the electricity sector, where regulation plays an important role due to the inherently monopolistic nature of the system and, in many cases, decisions are made without full information.

Assuming *perfect information* means that all participants have full and accurate knowledge of system conditions, market prices, and the actions of other at all times. In contrast, *information asymmetry* refers to situations where agents have unequal or partial access to relevant information. Even in regulated electricity markets, decisions are often made with incomplete knowledge due to technical limitations, market complexity, or institutional barriers. These assumptions strongly affect the design and performance of coordination schemes, influencing market efficiency, agent strategies, and system reliability.

Although some studies still rely on strong information symmetry for simplicity or analytical tractability (13.1%), a growing number of studies recognize the importance of limited foresight, partial observability, and decentralized data access—especially in distributed flexibility markets (86.9%). Distinguishing between these modelling choices is essential to understand the applicability of findings to real-world implementations, especially as flexibility becomes more distributed, dynamic, and embedded in increasingly complex local contexts.

3.3.3. Grid Constraints

The treatment of grid constraints in flexibility modelling varies widely across the literature, reflecting the trade-off between physical realism and computational feasibility.

Based on our review, we classify grid constraints into the following five groups, from explicit modelling to complete omission:

- **Detailed grid constraints**: These studies incorporate full power flow models, typically using IEEE standard test systems (e.g., 13, 33, or 69-bus systems [98]) or advanced test cases like Simbench [99]. Formulations such as AC-OPF, DC-OPF [100], and LinDistFlow [101] are employed to integrate line limits, voltage constraints, and nodal balances directly into the optimization process. Flexibility is treated as a control variable constraint by network states, allowing spatial and temporal feasibility assessments.
- **Linear or simplified approximations**: This group uses reduced grid models, including linear approximations [102] and clustering [8]. These techniques are common in studies focusing on aggregation strategies or market design, where full power flow modelling is computationally prohibitive.
- **Post-optimization validation**: Some studies exclude grid constraints during optimization, but validate results afterward through power flow simulations [103]. This ensures physical feasibility without embedding complexity in the main model.
- **Narrative or qualitative consideration**: These works acknowledge grid limitations, such as voltage, congestion, or capacity problems, but do not include mathematical representation. Often focused on qualitative insights, market design concepts, or regulatory or institutional frameworks, this group accounts for 61.3% (149) of the reviewed articles.
- **No consideration of grid constraints**: A total of 62 studies (25.5%) omit any reference to grid limitations, focusing on market mechanisms, actor behaviour, or economic outcomes. While useful for exploratory modelling, this omission reduces operational realism, especially when flexibility is intended for grid services like congestion management and voltage control.

Overall, there is growing recognition of the importance of physically grounded models. However, the detailed integration of grid constraints remains limited to a minority of technically orientated papers, while simplifications and omissions still dominate in market-oriented and actor-centric studies.

3.3.4. Tariffs

Tariff structures are central to flexibility market design. They shape the economic signals and incentives that drive flexibility activation. The literature reveals five types of tariffs used in modelling, each based on different assumptions regarding market structure, cost allocation, and user behaviour. These categories are summarized in Table 2.

Table 2. Tariffs.

Category	References
ToU and dynamic tariffs	[2,9,16,18,20,25,27,32,50,68,104–109]
Wholesale electricity market prices	[8,14,31,43,46,56,78,81,84,102,110–118]
Network access tariffs	[3,15,28,33,41,53,55,66,72,74,89,91,95,119–128]
Hybrid remuneration schemes	[6,45,58,62,129–143]
Tariffs as operational signals	[4,7,12,48,59,79,144–156]

The most common tariffs are **Time-of-Use (ToU) and dynamic tariffs**, which provide explicit signals to activate flexibility, particularly at the household or community level. These are often modelled as hourly or price-responsive incentives and are used in agent-

based simulations or comparative assessments across regulatory contexts. ToU tariffs are central to studies focusing on demand-side flexibility and customer-level participation.

A second group relies on **wholesale electricity market prices** (e.g., day-ahead, real-time, nodal, or marginal prices) as implicit activation signals. These studies assume that market-clearing prices can guide resource allocation without the need for regulated tariffs. Such approaches are prevalent in studies of market integration and co-optimization strategies.

A third set of studies models **network access tariffs**, including Distribution Use-of-System (DUoS), Transmission Network Use-of-System (TNUoS), and Balancing Services Use-of-System (BSUoS) charges. These are often analyzed in local market settings to assess how grid fees interact with flexibility incentives.

More advanced models introduce **hybrid remuneration schemes**, which combine capacity/energy payments (EUR/MW/year) with activation-based payments (EUR/MWh). These approaches aim to reflect the dual value of flexibility as both a capacity and an energy product and are common in procurement and ancillary service models.

Finally, some studies use **tariffs as operational signals** within system-level designs without modelling them explicitly. These include indirect incentives, such as avoided grid upgrades and congestion cost reductions, and are typically found in planning or conceptual frameworks.

This diversity of tariffs reflects the ongoing experimentation and regulatory evolution in flexibility market design but also exposes limitations: simplified price-based signals dominate and standardization is lacking. Advancing towards more realistic representations of tariff structures would strengthen comparability and policy relevance.

3.3.5. Modelling Approaches and Algorithms

Computational cost significantly affects how flexibility is represented, coordinated, and evaluated. Different modelling approaches address specific needs from redispatch optimization and strategic behaviour to coordination under uncertainty. Table 3 summarizes the main techniques used in the literature and their application domains.

Table 3. Modelling approaches and algorithms.

Category	References
Conventional optimization algorithms	[12,15,18,19,21,25,29,30,33,34,37,38,44,48,51,54,61,62,66,67,69,71,73,74,76,77,79,80,84,89,91,98,103,105,106,111,117,119,125,131–134,136,137,140,141,143,147,149,157–180]
Game-theoretic and equilibrium models	[42,83,159,161,181]
Agent-based models	[27,63,83,89,103,167]
Machine learning and heuristic methods	[18,40,96,103,182,183]
Distributed optimization techniques	[41,76,93,126]
Stochastic optimization methods	[64,66,93,117,118,121,172,184–186]

Deterministic optimization: Linear Programming (LP) and Mixed Integer Linear Programming (MILP) are the most widely used methods, particularly for dispatch, market clearing, and flexibility scheduling in both centralized and decentralized settings. Their strength lies in their robustness and transparency, making them ideal for local markets and the co-optimization of resources.

Game-theoretic and equilibrium models: These algorithms are employed to analyze strategic interactions among market participants, such as aggregators and consumers in competitive environments. However, their high computational complexity and limited scalability often restrict their application to conceptual analyses or simplified simulations. Their value lies in market efficiency assessment and mechanism design under rational decision-making assumptions.

Agent-based models: ABMs are used to simulate decentralized, heterogeneous systems where behaviour emerges from interaction rules rather than optimization. They are relevant for peer-to-peer flexibility markets, multi-agent negotiations, and energy community initiatives, often incorporating bounded rationality and partial information.

Machine learning and heuristic models: These are applied to tasks such as demand forecasting, clustering, and pattern recognition. While promising for system adaptation and user profiling, their use in core market functions remains limited and largely exploratory.

Distributed optimization: Used to coordinate agents in large-scale system with privacy or communication constraints, these methods allow problem decomposition across TSO–DSO boundaries or among distributed DERs. A notable sample of papers applies Alternating Direction Method of Multipliers (ADMMs). These approaches facilitate real-time communication among agents with limited information sharing.

Stochastic optimization: These approaches incorporate uncertainty explicitly, making them suitable for systems with high renewable penetration, variable demand, user behaviour, and price volatility. These models introduce probabilistic scenarios and risk-adjusted decision making, making them highly relevant for real-world planning. Their benefits include enhanced system reliability and robustness under uncertainty. However, the high computational cost—especially when many scenarios are modelled—limits their real-time applicability unless simplified or relaxed versions are used.

In sum, the choice of algorithm reflects not only technical priorities, but also the modelling philosophy (e.g., strategic vs. passive agents, centralized vs. distributed control). A growing number of studies adopt hybrid approaches, combining optimization, simulation, and machine learning to better capture the complexity of flexibility markets.

3.3.6. Interoperability

Interoperability is essential for enabling seamless communication and coordination among actors, platforms, and systems in flexibility markets. It supports the integration of distributed resources, the automation of demand response, and the scalability of local market architectures. However, more than 60% of the reviewed studies do not mention any communication standard, interoperability protocol, or structured architecture. This omission is especially common in methodological reviews, theoretical models, and studies focused on tariffs or behavioural responses. The absence of interoperable frameworks raises concerns about replicability and real-world applicability—particularly as flexibility becomes more decentralized and multi-actor by design.

Among the works that do address interoperability, **OpenADR** (*Open Automated Demand Response*) stands out as the most frequently cited standard. It appears in pilot projects that involve direct aggregator–DSO communication or demand-side coordination [1,23,43,44,79,89,112,126,159,160,179,187,188]. **USEF** (*Universal Smart Energy Framework*) is also widely referenced, providing a structured framework for market roles and information exchange in distributed flexibility ecosystems [13,55,68,132,154,156,189,190].

At the technical layer, standards such as **IEC 61850** and **IEC 62559-2** are used in studies related to substation automation or control-layer integration [191,192], while the CIM (*Common Information Model*) [150,193] and SGAM (*Smart Grid Architecture Model*) are more common in information modelling and platform design. These frameworks help build interoperable, scalable market platforms, although their practical deployment remains limited.

Some studies analyze interoperability more systematically. For example, ref. [187] compares technical and contractual approaches, showing how standardized protocols can enhance market efficiency and replicability. The ORFLEX project [44] goes further by embedding interoperability into platform design using existing standards.

Overall, while OpenADR and USEF serve as leading references, interoperability in flexibility modelling remains an exploratory or secondary consideration in most of the literature. The current reliance on proprietary solutions and ad hoc interfaces suggests a need for more structured adoption of interoperability standards, especially as local markets scale and require integration across heterogeneous systems and actors.

3.3.7. Technology Readiness Level

The TRL scale is a standard framework for assessing the maturity of technologies, from conceptual ideas to fully operational systems. Based on the reviewed studies, flexibility market solutions span the full TRL spectrum, though most remain in an intermediate stage. To ensure consistency across heterogeneous studies, we classify each contribution by the highest TRL, evidenced through the following: (i) nature of validation (simulation/lab/field), (ii) data provenance, (iii) system integration, and (iv) stakeholder involvement:

TRL 1–3: Research and Conceptualization: This category includes basic principles and concept formulation. Technologies at this stage are theoretical or under lab-scale experimentation. A considerable number of studies fall into this category, reflecting conceptual work or early-stage modelling with limited technical implementation. This category applies to theoretical models, proof-of-concept code, and market roles.

TRL 4–6: Prototype and Demonstration: This group involves technology validation in relevant environments and simulated settings such as pilots or hardware/software-in the loop; synthetic or limited operational data; and constrained grid models. This is the category with most contributions in the review, often linked to EU pilot projects and regulatory sandboxes that test flexibility mechanisms in controlled conditions.

TRL 7–9: Pre-Commercial and Operational Deployment: These levels correspond to real-world implementation, from system demonstration to full commercial operation. This applies to real customers/assets; interoperable platform; and measurable KPIs. Only a small share of studies reaches this level, indicating limited large-scale deployment.

The findings reveal that flexibility market technologies are still under development, moving from conceptual ideas to operational maturity. Although the foundation is robust and demonstrators are increasingly available, widespread deployment at TRL 8–9 is still rare, largely due to regulatory fragmentation, interoperability challenges, and evolving market structures. Most contributions sit in TRLs 4–6 with robust prototyping and controlled pilots; TRLs 1–3 show novel algorithms, tariff designs, or market-clearing schemes validated only in simulation. TRLs 7–9 appear in a smaller subset, and their patterns include DSO-led local flexibility tenders mitigating MV/LV congestion with verified activation and settlement.

3.4. Market Participants and Enablers

3.4.1. Aggregation

Aggregation emerges as the backbone of flexibility market designs. Aggregators or Flexibility Service Providers (FSPs) are present in over 110 studies, acting as commercial intermediaries, technical coordinators, and often the only interface with DSOs or TSOs. Their role spans from the real-time dispatch of DERs to bidding on behalf of consumers in various market layers.

A growing number of studies focus on energy communities, which represent a promising model for collective participation. These structures offer scalability, social acceptance, and bottom-up innovation, especially when combined with P2P trading or cooperative platforms.

Households and residential actors are also gaining ground, particularly when supported by digital infrastructure, automation, and well-designed incentive schemes. Mean-

while, the industrial and SME sector provides high-capacity flexibility but often requires custom aggregation and tailored regulatory frameworks.

The literature reflects a trend toward hierarchical aggregation architectures, moving from device-level management (e.g., appliances and individual batteries) to virtual power plants (VPPs), distributed platforms, and interoperable multi-agent systems. This hierarchical aggregation enables more scalable and integrated flexibility solutions.

3.4.2. Time Scale

The time scale at which flexibility is modelled and activated is key in electricity market design and operation. It shapes the responsiveness required from flexible resources, the coordination mechanisms, and types of actors involved. Across the literature, time scales range from sub-hourly real-time signals to long-term planning horizons. To structure the analysis, we group the studies into the following four main categories: *Real time and Intra-day*, *Day ahead*, *Medium term*, and *Long term* (See Table 4).

Table 4. Flexibility timescales and corresponding measures.

Timescale	Purpose	Applications
Long term	Strategic planning and system adequacy	Annual system planning, capacity remuneration mechanisms, regulatory tariffs, and incentive schemes
Medium term	Anticipatory scheduling to address seasonal variability	Seasonal flexibility assessments, long-term market structuring
Short term	Short-term market operation and adaptability to forecast uncertainties	Day-ahead and intraday market participation, transition from zonal to nodal pricing, reduction in gate closure intervals
Very short term	Real-time operational responsiveness and frequency stability	Real-time balancing services, frequency containment and restoration reserves (FCRs, FRRs), fast frequency response (FFR), inertia support

Very short term: This category includes studies focused on real-time, intra-day, or balancing operations, often involving fast-response flexibility. These models are essential for capturing operational challenges, system stability, and immediate activation of resources, particularly relevant in balancing markets and near-term congestion management.

Short term: Articles in this group rely primarily on day-ahead market structures, where flexibility is scheduled based on forecasts and market signals from the previous day. This timescale is common in aggregator models and demand response schemes that require some level of planning and coordination in advance.

Medium term: These studies bridge planning and operational layers by combining day-ahead and real-time or intra-day mechanisms. They reflect hybrid coordination approaches, where flexibility is first scheduled and later adjusted, providing a more realistic picture of market dynamics under uncertainty.

Long term: This group encompasses models spanning from hourly to seasonal or yearly horizons, often linked to planning, market design, or regulatory strategy. These studies address structural questions, long-term investment signals, and the integration of flexibility into evolving system architectures.

3.4.3. Agent

The types of agents considered in flexibility market models reveal the perspective and system level of each study. Depending on whether the focus is technical, market-based, or regulatory, different actors are included in the analysis—ranging from individual consumers to centralized system operators. To structure this dimension, we classify the literature into the following five categories: *TSO/DSO-centred*, *Aggregator-focused*, *Prosumer and end-user inclusive*, *Multi-actor coordination*, and *Institutional/systemic*. This classification helps interpret how actor complexity and decentralization shape flexibility mechanisms.

TSO/DSO-centred: These studies focus on transmission and distribution system operators as key players in flexibility activation. They typically address grid operation, congestion management, and system-level balancing. Models often assume centralized control and coordination logic, especially in technical or optimization-based analyses.

Aggregator-focused: A large body of literature treats aggregators as the primary interface between distributed flexibility and markets. These models centre on bidding strategies, coordination schemes, and participation in wholesale or local flexibility markets. The aggregator often acts as the sole intermediary without direct modelling of individual users.

Prosumer and end-user inclusive: This group includes models that explicitly consider consumers, prosumers, and small-scale users, often in combination with aggregators or DSOs. They are common in studies on demand response, behavioural modelling, and peer-to-peer trading, where decentralization and user participation are central.

Multi-actor coordination: These studies reflect complex interactions among multiple agents—aggregators, DSOs, TSOs, BRPs, retailers, platforms, and regulators. They typically explore coordination mechanisms, market roles, and value distribution. This group is prevalent in conceptual frameworks, regulatory analysis, and large-scale system simulations.

Institutional/Systemic: A smaller subset abstracts away from operational actors and focuses on institutional roles like market operators, planners, and regulators. These models address the governance, architecture, and business model implications of flexibility markets rather than detailed operational behaviour.

In conclusion, the representation of agents in flexibility models reveals a clear trend toward greater complexity and decentralization. While system operators and aggregators remain central, recent models incorporate a broader range of stakeholders, reflecting the complexity of realistic flexibility markets.

3.5. Transactional and Coordination Aspects

The coordination of distributed flexibility is not only a technical challenge, but also a matter of market design, strategic incentives, and institutional roles. As flexibility becomes a core component of power system operation, it is increasingly important to understand how agents interact, how decisions are coordinated, and how transactions are shaped under different governance and computational models. This section explores the following three key dimensions that underpin these aspects: the coordination paradigms used to structure agent interaction (Section 3.5.1), the optimization levels that determine how decisions are computed and communicated (Section 3.5.2), and the treatment of strategic behaviour, which influences market robustness and fairness (Section 3.5.3). Together, these perspectives offer a comprehensive view of how flexibility is operationalized within complex, multi-actor energy systems. This section is closely aligned with the TEAM framework, particularly its focus on Actors, Transactions, and Mechanisms. The identified coordination and transactional features reflect how responsibilities are distributed among stakeholders, how decisions are negotiated or delegated, and how systems are designed to ensure interoperability, scalability, and incentive alignment. Together, these perspectives offer a comprehensive view of how flexibility is operationalized within complex, multi-actor energy systems.

3.5.1. Coordination Paradigms

The coordination of flexibility among agents is a critical design dimension that shapes market architecture, communication needs, and governance responsibilities. The literature

identifies four dominant paradigms, each with distinct implications, presented in Figure 2 and Table 5, as follows:

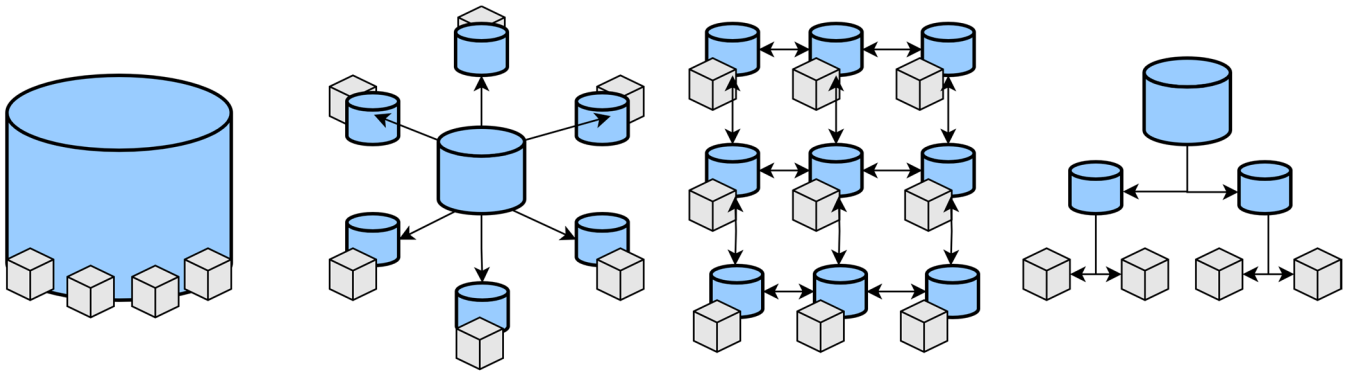


Figure 2. Coordination paradigms in flexibility markets.

Table 5. Coordination paradigms: comparison of key features.

Paradigm	Key Coordinator	Information Flow	Pros	Cons
Centralized	TSO/DSO	One-way	Efficiency, control	Scalability, limited local autonomy
Decentralized	No single entity	Peer-to-peer	Scalability, autonomy	Coordination, system integration
Hierarchical	Multi-layer	Sequential	Modularity, coordination	Interface complexity, latency
Hybrid	Mixed	Multi-directional	Flexibility, realism	Governance, standardization need

Centralized: In the centralized paradigm (Figure 2a), a single entity—typically the TSO or DSO—is responsible for collecting information, optimizing system operation, and issuing dispatch instructions to all flexibility providers. This model ensures global efficiency, full network visibility, and is often used in security-constrained optimal power flow or balancing mechanisms. However, it requires high-communication infrastructure, may suffer from scalability issues, and can limit local autonomy. This is the second most prominent group in the review: 79 articles belong to this category.

Hybrid: The hybrid paradigm (Figure 2b) combines elements of centralized, decentralized, and hierarchical coordination. Often seen in pilot projects or multi-agent simulations, hybrid models seek to balance efficiency, resilience, and practical deployment constraints. Examples include systems where aggregators trade locally but must comply with global constraints imposed by DSOs and local flexibility markets with central price clearing. While promising, hybrid coordination introduces complex governance, multiple control layers and demands advanced communication and data models. Only references [160,166,179] suggest or apply to this category.

Decentralized: Distributed systems (Figure 2c) allow prosumers, aggregators, or devices to interact directly, often using peer-to-peer (P2P) protocols or local markets. This approach favours scalability, local optimization, and user empowerment. It reduces the need for a central authority but introduces challenges such as information asymmetry, coordination inefficiencies, and difficulty in enforcing system-wide constraints. This is the most prominent group in the review: 108 articles belong to this category.

Hierarchical: Hierarchical models structure the system into layers, where decisions are made sequentially (Figure 2d). For example, the TSO ensures system adequacy, while DSOs coordinate local resources and aggregators optimize behind-the-metre assets. This model balances central oversight with local responsiveness, enabling modular control, data privacy, and coordinated network management. However, it requires well-defined

interfaces, clear role separation, and strong interoperability standards. This is the third most prominent group in the review: 53 articles belong to this category.

3.5.2. Optimization Level of Coordination

Coordination in flexibility markets is not only a matter of system architecture, but also of computational design. The way in which optimization is performed—how decisions are computed, by whom, and with what information—has a significant impact on system efficiency, scalability, and real-world applicability. The literature identifies several levels of optimization sophistication, as follows:

- **Global optimization**: Global or system-wide optimization typically appears in centralized or bilevel frameworks, where a single authority (e.g., TSO or DSO) optimizes the activation and allocation of all available flexibility resources. These models aim to maximize social welfare, minimize system costs, and enforce network constraints holistically. They offer high efficiency and clear visibility over system dynamics but rely on complete information and pose scalability challenges in large, distributed systems.
- **Distributed optimization**: In contrast, distributed optimization leverages multi-agent systems, where each actor (aggregator, prosumer, DSO, etc.) solves its own local problem, potentially exchanging information through a coordination protocol. Methods include dual decomposition, Alternating Direction Method Of Multipliers (ADMM), and iterative pricing schemes. This approach reflects real-world decentralization and improves scalability, but requires convergence guarantees, robust communication, and often approximate solutions.
- **Rule-based heuristics**: Many pilot projects, regulatory sandboxes, and early-stage demonstrations rely on heuristic or rule-based methods for coordination. These may involve static priorities, time-of-use rules, and simple threshold-based activation. While not optimal in a mathematical sense, heuristics are pragmatic, transparent, and easily implementable, making them useful in uncertain or evolving regulatory contexts.
- **Stackelberg and game-theoretic models**: To capture strategic behaviour or sequential decision making, some studies use Stackelberg games, leader–follower models, and other game-theoretic frameworks. These allow one agent (e.g., a DSO) to anticipate responses from others (e.g., aggregators) and design coordination accordingly. Such models are valuable for studying incentives and market power but are computationally intensive and often limited to theoretical analysis or stylized case studies.

The choice of optimization level reflects trade-offs between mathematical optimality, real-world implementability, and regulatory maturity. As flexibility markets evolve, there is growing interest in hybrid approaches—combining centralized forecasting with local decision making or embedding heuristics within distributed optimization frameworks—to strike a balance between control and scalability.

3.5.3. Strategic Behaviour

Strategic behaviour refers to the ability of market participants to manipulate their actions or information to gain an economic advantage. This issue is particularly relevant in flexibility markets, where asymmetric information, temporal coupling, and forecast-based baselines can create opportunities for gaming or inefficient outcomes. The literature reveals a wide spectrum of approaches to this challenge, as follows:

Explicit strategic modelling: Some studies adopt a formal treatment of strategic behaviour through game theory, bilevel optimization, or mechanism design. These models typically involve agents anticipating the responses of others or manipulating market signals, such as submitting false availability, withholding flexibility, and misrepresenting costs.

Such approaches allow for a detailed understanding of incentive misalignments but are computationally demanding and rarely used in large-scale simulations.

Strategic-proof market design: Some works take a design-oriented approach, proposing incentive-compatible mechanisms that are resistant to gaming, even without simulating strategic agents explicitly. This includes mechanisms like pay-as-bid with verification, priority rules, and penalty schemes that discourage opportunistic behaviour. These contributions bridge theory and practice by embedding safeguards directly into market rules.

Acknowledged but not modelled: A broader segment of the literature recognizes the existence of strategic risks—such as baseline manipulation, false flexibility offers, and imbalanced bidding—but does not integrate them into the modelling framework. These studies may mention the issue in discussion sections or suggest mitigation strategies yet treat agents as non-strategic during simulation. This approach is often a trade-off between realism and model tractability.

Simplified or ignored: Many technical or optimization-based papers abstract away from strategic behaviour entirely, assuming agents act as passive responders following predefined rules or price signals. While this simplification eases implementation and comparison across scenarios, it risks overestimating market efficiency and underestimating vulnerabilities to manipulation.

This diversity in treatment reveals a gap between theoretical awareness of strategic interaction and its practical integration into simulation tools or policy evaluations. As local and distributed flexibility markets grow in importance, incorporating realistic behavioural assumptions will be essential to ensure trust, efficiency, and robustness in market outcomes.

3.6. Business Model Analysis

The successful deployment and scalability of flexibility markets depend not only on technical and regulatory design, but also on viable business models. This section analyses the literature through the following five key components from the Business Model Canvas: value proposition, customer segments, delivery channels, cost structures, and revenue streams. Understanding these dimensions provides insights into how flexibility services are being conceptualized, implemented, and monetized across Europe.

In the reviewed literature, we identified seven articles that explicitly refer to business models, encompassing a broad diversity of perspectives. These include models centred around **Distribution System Operators (DSOs)** [3,13], **aggregators** [14], **market platform operators** [65,192,194], and other emerging actors [12]. The conceptualization of the business model varies depending on the stakeholder's role, the market structure, and the type of flexibility resource involved. This section aims to synthesize and unify these heterogeneous business model approaches, offering a comparative analysis that highlights common patterns, innovations, and open challenges.

3.6.1. Value Proposition

Across the reviewed studies, value propositions are centred on leveraging flexibility to enhance grid operation, defer costly investments, and create new economic opportunities. Although the terminology and emphasis vary, the propositions can be grouped into the following six dominant themes:

DSO Empowerment and Operational Security: Many articles highlight the role of flexibility in enabling Distribution System Operators (DSOs) to manage grid operations more securely and efficiently. These models often emphasize secure procurement, reduced capital expenditure (CAPEX), and increased operational adaptability without the need for planning physical reinforcement.

DER and Prosumer Market Participation: A significant portion of the literature focuses on unlocking value for distributed energy resources (DERs) and prosumers. This includes enabling access to flexibility markets, improving participation through better scheduling and market design, and creating value via aggregation and digital platforms.

Local Congestion Management: Another common value proposition revolves around LFMs as tools for congestion mitigation. These contributions underline the efficiency gains from the localized dispatch of flexible assets, often linked to market-based mechanisms and distributed resources.

System-Level Efficiency and Risk Mitigation: Several studies emphasize coordinated TSO–DSO operation and system-wide efficiency. Proposals here often mention improved procurement, optimized allocation under uncertainty, and cost-effective use of flexibility to balance the grid.

Renewable Integration and Thermal Flexibility: A subset of the literature focuses on enhancing renewable energy integration using thermal inertia, flexible load control, and demand response. These models emphasize flexibility as a facilitator of higher RES penetration and reduced curtailment.

Grid Reliability, Cost Reduction, and User Empowerment: Finally, many value propositions address the potential of flexibility to reduce grid stress, improve reliability, and lower operational costs. These studies also highlight the empowerment of end-users and microgrids to contribute to grid stability and receive economic compensation.

In summary, the value propositions identified in the literature demonstrate a broad consensus around flexibility as an enabler of cost-effective, secure, and decentralized grid management, as well as a source of new value streams for system operators, aggregators, and prosumers. This diversity of perspectives underscores the need for adaptable and stakeholder-specific business models in the evolving energy landscape.

3.6.2. Customer Segments

Customer segments vary depending on the main actor and their specific value proposition. While some studies explicitly define customer segments within a Business Model Canvas, this analysis extends to all reviewed articles to ensure consistency. Segments are categorized based on the proposing agent, allowing foe a structured view of the client landscape across flexibility business models.

Aggregator-centred models [146,182] are the most frequently observed. These models typically target residential consumers and prosumers, enabling them to monetize their flexibility through demand-side participation. Aggregators also serve system operators (DSOs and TSOs) by offering bundled flexibility services for balancing and congestion management, as well as market operators and BRPs [122] through optimization and risk mitigation strategies. In some cases, commercial [105] and industrial [158,172] customers are also targeted, especially for large-scale demand response.

DSO-centred models [13,148] primarily focus on the procurement and coordination of local flexibility. Their customer segments commonly include aggregators, from whom DSOs acquire flexibility services, as well as residential communities and prosumers interacting via local flexibility markets. In certain models, DSOs also serve retailers and energy service companies (ESCOs) [7], acting as facilitators of distribution-level transactions and grid services.

In models where prosumers [169] or DER owners [192] are central actors, the customer base often includes platform providers and community aggregators. These models promote prosumer engagement in peer-to-peer trading or community-based flexibility services. They also highlight mutual value generation through market participation and local grid support, often facilitated by digital platforms or standardized protocols.

Several models propose **digital platforms** [23,194] that cater to multiple customer groups. These include DSOs and TSOs as flexibility buyers, aggregators and ESCOs as service providers, and municipalities or district operators as stakeholders in implementation. Some also target software developers or regulators, particularly when platforms aim to enhance interoperability, modularity, or replicability.

Overall, the literature presents a highly diverse set of customer segments aligned with different agent roles. While DSOs and aggregators dominate frequently, other actors such as prosumers, local energy communities, and industrial consumers are increasingly included. This multiplicity reflects the complexity of flexibility markets and the need for business models to be tailored to specific customer profiles, local conditions, and system needs.

3.6.3. Channels

The delivery channels through which flexibility services are offered and monetized vary significantly depending on the actor and their specific business model. These channels play a critical role in connecting flexibility providers with the actors that request flexibility—most often Distribution System Operators (DSOs), Transmission System Operators (TSOs), and market operators.

As detailed in [23], various commercial flexibility market platforms (FMPs) are already operational in Europe, each with its own structure, traded products, and user segments. This work provides an in-depth review of the main platforms, such as Piclo Flex, Flexible Power, NODES, Enedis, and OMIE, and clearly identifies who the requesting agents are (e.g., DSOs or TSOs) and which actors can participate as flexibility service providers (FSPs). These platforms cover a wide range of interaction modes, from tender-based procurement and capacity reservation to continuous market clearing mechanisms, often supported by APIs, smart contracts, or bilateral agreements.

In this broader review, aggregator-centred models appear most frequently. These rely on aggregator platforms that serve as interfaces between prosumers or flexible consumers and system operators. They often incorporate Home Energy Management Systems, virtual power plants, or multi-agent coordination algorithms to facilitate offer aggregation and optimization.

Market platforms—either centralized or local—are also central delivery channels. These include wholesale energy markets, balancing platforms, and dedicated LFMs. In these models, the aggregator or DSO frequently acts as an intermediary that manages qualification, bidding, dispatch, and settlement processes.

Additionally, the literature highlights flexibility platforms managed by system operators or market facilitators that support the entire flexibility procurement chain. These platforms often include functionality for user registration, product definition, asset qualification, bid submission, and post-delivery settlement. Notably, in some countries, regulation is moving towards requiring national-level platforms to prevent fragmentation and improve accessibility.

In community-oriented or prosumer-focused business models, local energy platforms and peer-to-peer (P2P) marketplaces are identified as emerging channels. These platforms allow local actors—such as cooperatives and energy communities—to interact with system needs while maintaining a degree of autonomy and flexibility in trading mechanisms.

Overall, while aggregator and market platforms dominate the current landscape, the variety of channels reflects the diversity of actors and configurations present in flexibility markets. The structure and maturity of each platform are directly influenced by the agent responsible for initiating the service and the regulatory environment in which it operates.

3.6.4. Cost Structure

Cost-related aspects are treated with varying depth across the reviewed literature. While some studies provide detailed breakdowns, many either omit cost modelling entirely or address it in broad terms. The main types of costs identified include capital expenditures (CAPEX) [90], such as investments in ICT platforms [114], energy storage systems [177], and retrofitting of devices [173]; operational expenditures (OPEX) [89], covering forecasting, market participation, DER activation, ICT maintenance [114], and user compensation [3]; and transaction or coordination costs, including aggregator infrastructure, data exchange, and incentive design. Additionally, some works consider flexibility-specific costs like battery degradation [155], load curtailment [143], and comfort penalties [3], although these are less frequently quantified.

In terms of modelling, cost structures are often simplified or assumed implicitly. Several simulation-based studies estimate economic impacts indirectly or rely on qualitative assessments. Only a minority of articles model costs comprehensively or include uncertainty-driven elements, such as baseline risk or market volatility. Moreover, trade-offs between CAPEX and OPEX are rarely discussed in depth, and indirect or hidden costs (e.g., governance, integration, and regulatory compliance) are typically overlooked. Despite these limitations, some emerging trends can be observed. There is increasing attention paid to ICT-related costs and platform development in local flexibility markets, and a gradual shift towards integrating cost components into agent-based models and optimization frameworks. A few studies explore stacked services and value streams, linking cost to broader system benefits, but overall, the treatment of cost structures remains fragmented and lacks standardization across the field.

In conclusion, while cost considerations are central to the viability and scalability of flexibility mechanisms, their treatment in the literature remains uneven and often superficial. The lack of standardized cost typologies and consistent modelling practices hinders cross-study comparability and limits the translation of findings into actionable insights. Advancing the field will require more transparent, granular, and integrated cost modelling that captures not only direct operational and investment costs, but also coordination, user engagement, and system-level impacts.

3.6.5. Revenue Streams

Revenue streams in flexibility business models exhibit a notable diversity, reflecting the heterogeneity of actors, regulatory contexts, and market maturity. A significant share of the articles analyzed refer to market-based revenues, including earnings from participation in energy markets [80], reserve capacity auctions [113], and balancing mechanisms [167]. These streams are particularly relevant for aggregators and prosumers who actively trade flexibility.

Another prominent category includes cost savings and avoided infrastructure investments [179], especially for DSOs who leverage flexibility to defer or replace costly grid reinforcements. This indirect monetization is often complemented by direct payments [3] for service provision, such as activation fees [178] and capacity availability payments from DSOs or TSOs [195].

Some models also integrate ancillary services revenues [127] or dynamic tariffs [109] that reward flexible behaviour. At the community level, incentives and shared benefits (e.g., lower bills and local market gains) play a role in reinforcing participation.

Finally, a subset of articles highlights emerging or experimental revenue models, including licencing fees for platform operators [196], transaction-based commissions, and policy-driven compensation schemes.

This broad landscape underscores the need for adaptable and transparent mechanisms that ensure fair compensation while aligning incentives across the flexibility ecosystem.

3.6.6. Actor-Specific Differentiation

A cross-cutting synthesis of the reviewed literature reveals clear differences in how value, costs, and risks are distributed among the main actors. Distribution System Operators (DSOs) typically benefit from deferred grid reinforcements and improved operational security, but they also face significant integration costs related to ICT systems, market platforms, and regulatory compliance. Several works applying the Business Model Canvas to DSOs highlight that these actors require clear procurement mechanisms and standardized procedures to translate avoided CAPEX into actionable business cases [109].

Aggregators, in turn, capture revenues by pooling distributed resources and offering bundled services to DSOs, TSOs, or market operators. However, their cost structures include coordination overhead, transaction costs, and compensation schemes for consumers [12,178]. The literature also shows that aggregators face asymmetric barriers depending on their role: supplier-affiliated aggregators can leverage existing contracts, while independent aggregators and those acting as Balance Responsible Parties (BRPs) encounter higher contractual complexity and liquidity risks [104].

End-users and prosumers usually obtain only modest financial benefits (bill reductions, incentives, or community gains) while assuming comfort or productivity trade-offs. Sector-specific cases—such as greenhouses and service-sector enterprises—highlight that user engagement is essential but economically fragile without transparent and fair compensation mechanisms [3,178].

Finally, the platform perspective shows that local flexibility ecosystems redistribute roles and risks across multi-sided actors. Platforms such as Piclo Flex, NODES, GOPACS, and FLEXGRID enable DSOs, TSOs, and aggregators to interact with prosumers, while imposing new forms of governance and transaction costs [83]. This actor-specific differentiation confirms that flexibility business models are not neutral: they redistribute costs and risks in ways that directly affect scalability, fairness, and long-term viability.

4. Discussion

This review provides a comprehensive synthesis of how flexibility markets are conceptualized, modelled, and assessed in the academic literature. The findings highlight important developments, but also reveal fragmentation, methodological gaps, and limited real-world applicability. In what follows, we critically discuss these insights in the following five interrelated dimensions: main findings, methodological weaknesses, thematic gaps, implications for practice and policy, and future research directions and priorities.

4.1. Main Findings and Emerging Patterns

The analysis reveals three dominant trends in the academic literature. First, modelling approaches tend to prioritize technical and economic optimization. Most studies focus on aggregator-based coordination, centralized dispatch, and deterministic simulations. The preference for linear programming, MILP, and agent-based models reflects a clear effort to capture operational and market dynamics under simplified assumptions. These methods enable operational precision, but rely on simplified assumptions, such as perfect foresight, static pricing, and centralized decision making. For example, Ref. [152] develops an ADMM-based market-clearing model tailored to distributed flexibility markets. While the algorithm supports scalability and decomposition, it operates under idealized assumptions, excluding real-time variability and uncertainty and limiting its robustness under realistic dynamics. In a similar vein, Ref. [149] applies MILP algorithms to compare the performance

of static time-of-use tariffs based on average prices from Croatia and Denmark. Although the comparison of different tariff schemes provides useful insights, the use of mean values prevents the model from capturing intraday price fluctuations and how these influence real world flexibility activation and strategy selection. A more detailed case is presented in [101], where MILP algorithms are used in combination with Distribution Use-of-System tariffs that include networks constraints and node-level capacity limits. The test scenario involves a medium-voltage feeder with three consumers and an EV charging station, using spot market prices from a summer and winter day, plus a fixed network charge. While this is one of the few models to integrate both tariff signals and physical constraints at the node level, it still relies on a static simulation framework with no real-time feedback. A dynamic or rolling horizon approach could have captured operational adjustments more accurately and allowed for better evaluation of time-sensitive flexibility.

Second, flexibility is rarely treated as a multidimensional concept. While several metrics are proposed, they tend to focus on technical parameters (e.g., ramp rate and power availability) or economic signals (e.g., activation costs and market revenues). Very few studies include social acceptance, institutional roles, or behavioural dynamics. As a result, most models underestimate the complexity of implementing flexibility services in real-world settings, particularly at the distribution level. For example, study [134] introduces the notion of utility for prosumers and frames flexibility as a contributor to overall social welfare. However, the analysis is grounded entirely in economic theory, without addressing flexibility as a tool for citizen empowerment, collective agency, or social cohesion. Similarly, Ref. [28] acknowledges the potential welfare benefits of flexibility but limits its analysis to efficiency gains derived from coordination between TSO and DSO. Social impacts are mentioned only in passing and are not captured in the modelling framework. In contrast, [109] stands out by incorporating distributional effects into the tariff design process. The study evaluates how static ToU and fixed tariffs affect six different income groups in the UK, explicitly accounting for demographic diversity, household routines, and time availability. Crucially, it finds that low-income users are less likely to benefit from price-based flexibility schemes due to lower adaptability and more constrained energy usage patterns. These examples highlight an important conclusion: while flexibility markets are often promoted as inclusive and efficient, the lack of multidimensional modelling risks reinforcing existing inequalities or excluding vulnerable groups. Incorporating behavioural and socio-economic heterogeneity is essential not only for accuracy, but also for fairness and legitimacy. Moreover, these aspects are particularly important in the design of local flexibility mechanisms, energy communities, and demand response programmes where user engagement and trust are key to adoption.

Third, the business dimension of flexibility markets remains significantly underdeveloped. Despite growing recognition of the importance of business models and actor-specific value creation, only a small number of papers conduct a structured analysis using frameworks like the Business Model Canvas. Most cost structures are treated qualitatively or omitted entirely. Revenue mechanisms are simplified, often relying on idealized markets or static price signals. This gap is especially relevant considering the growing interest in deploying flexibility services in local energy communities and multi-actor environments. A notable example is provided [42], where the cost of providing flexibility is explicitly calculated across the following five market configurations: disjoint transmission-level market, disjoint distribution-level market, common market model, fragmented market model, and multi-level market model. The study uses an ADMM-based optimization framework that includes grid constraints and models interactions between high-voltage IEEE test systems (14-bus) and multiple distribution networks (18-bus, 69-bus, and 144-bus Matpower cases). It estimates flexibility costs ranging from 10 to 15 EUR/MWh for upward regulation and

45 to 50 EUR/MWh for downward regulation, depending on market structure. While this approach is valuable for benchmarking system-level coordination costs, it still omits the broader set of economic components required to operationalize flexibility, such as ICT investments, communication infrastructure, hardware upgrades, and transaction costs. These elements are often decisive in determining the scalability and replicability of flexibility solutions, particularly in local or decentralized settings. Across the corpus, there is a notable absence of studies that quantify the full cost stack of flexibility deployment. Although national plans, demonstrator reports, and grey literature often address implementation costs in detail, these sources were excluded from this review to maintain academic rigour and focus on peer-reviewed research. This may partially explain the gap. Nevertheless, it underscores a major limitation of the scientific discourse: without addressing investment needs, operational overheads, and cost recovery mechanisms, flexibility models will be disconnected from market and policy realities. Moreover, the differentiation of actor roles has direct implications for both policy design and market implementation. For DSOs, avoided investment is meaningful only if regulatory frameworks allow for the recovery of ICT and compliance costs, as highlighted in business model applications [13]. For aggregators, the choice of role strongly conditions feasibility: supplier-affiliated aggregators benefit from simpler contractual arrangements, while independent aggregators face higher transaction costs and contractual burdens, which may hinder competition [14]. Recent reviews of commercial platforms further illustrate how rules redistribute risks. For example, NODES applies explicit penalties for non-delivery, shifting operational risk to aggregators and prosumers [23], whereas Piclo Flex provides standardized APIs that reduce transaction costs and create clearer settlement procedures. In contrast, national tenders such as those of Enedis show that limited economic value and complex processes can discourage participation [23]. These examples underline that the success of flexibility markets depends not only on technical and regulatory alignment, but also on transparent business models where costs and revenues are fairly allocated across DSOs, aggregators, and end-users.

4.2. Methodological Weaknesses

The review also exposes key methodological limitations across the literature. First, uncertainty is rarely integrated into the modelling process of flexibility markets. Only a limited number of studies incorporate probabilistic methods, scenario analysis, or stochastic optimization. This omission is problematic in a domain where variability—of price signals, user response, and renewable output—is intrinsic. Deterministic models may overestimate flexibility potential and misrepresent risk exposure. Some studies attempt to explore variability using scenario-based modelling. For example, Ref. [124] investigates how different levels of financial incentives influence user participation by defining four distinct behavioural scenarios. However, these are still deterministic simulations, and do not reflect probabilistic distributions or stochastic user response. Similarly, Ref. [135] uses predefined winter and summer day profiles to assess different operational strategies for distributed energy resources, but again, the model assumes fixed boundary conditions and lacks any formal treatment of uncertainty in inputs or system evolution. A more robust approach is presented in [31], which employs Monte Carlo simulations to model system-level variability, including both renewable output and load uncertainty. Crucially, this study also integrates grid constraints and quantifies the number of violations across simulated trajectories. Flexibility is then deployed as a corrective mechanism to restore feasibility, providing a much more realistic picture oof its operational value under uncertainty. Beyond this case, very few studies systematically address uncertainty in the modelling of flexibility services. The lack of stochastic or robust optimization signals a methodological gap that limits the applicability of findings for real-world decision making. Further models must

move beyond deterministic planning to capture the probabilistic nature of flexible system operation, especially in decentralized and renewable-rich contexts.

Second, the integration of real-time data remains scarce in flexibility market models. Most studies rely on static assumptions, such as day-ahead schedules, average tariff values, and fixed demand and generation profiles, which prevent capturing intra-day variability and dynamic adjustments. Only a few contributions adopt rolling-horizon optimization, distributed control, or stochastic methods that can process real-time inputs from sensors, metres, and market platforms. This gap is critical, as flexibility activation and verification depend on near real-time signals (e.g., grid congestion status, updated forecasts, and imbalance prices). Without explicit integration of these data streams, modelling frameworks risk overestimating available flexibility and underrepresenting the operational constraints faced by DSOs, aggregators, and end-users. Advancing towards TRLs 7–9 deployments will, therefore, require simulation and validation environments that incorporate real-time feedback, interoperability with ICT platforms, and dynamic settlement procedures.

Third, a further methodological consideration concerns the choice between game-theoretic and agent-based modelling approaches in the study of flexibility markets. Game-theoretic models are particularly effective for analyzing strategic behaviour, incentive design, and the fair allocation of costs and benefits across actors. For example, recent studies have applied cooperative game theory and the Shapley value to optimize electricity market outcomes and ensure equitable benefit sharing among heterogeneous players [197]. However, these approaches often rely on simplifying assumptions such as complete information and rational behaviour, which may not fully capture the operational complexity of real-world flexibility markets. By contrast, agent-based models allow for the simulation of diverse actors, bounded rationality, learning, and dynamic responses to uncertainty, offering a richer representation of market performance under realistic conditions. Their drawback lies in calibration and generalizability, as results can be sensitive to specific scenarios. Taken together, these approaches are complementary: game theory can inform the design of rules and payment mechanisms, while agent-based simulations can stress-test their performance under uncertainty and behavioural diversity.

Forth, agent behaviour is typically idealized. Most simulations assume rational or rule-based behaviour, without accounting for strategic manipulation, comfort thresholds, and bounded rationality. This weakens the applicability of the models to real-life conditions, where actors have asymmetric information, conflicting objectives, and varying levels of engagement, as presented in Sections 3.3.1 and 3.3.2. A promising exception is found in [96], which develops a secondary flexibility market based on agent-based architecture that explicitly models different player types, strategies, and relationships. The framework is applied to a modified IEEE-13 node distribution network with demand flexibility distributed over multiple periods of the day. This study shows that flexibility can be coordinated across multiple microgrids with diverse resources, including algo technical constraints to ensure that market outcomes remain feasible within the physical limits of the network, and reveals that agents with limited flexibility capacity may face economic disadvantages. These features raise the level of realism and operational relevance compared to traditional models.

Fifth, grid constraints are often ignored or simplified. Less than one-third of the studies include grid-level parameters such as voltage limits and line capacities. When considered, they are often post-processed rather than embedded in the optimization. This reduces the credibility of findings related to congestion management or local balancing.

Sixth, interoperability is overlooked in most cases. Despite the centrality of ICT platforms and data exchange in flexibility market operation, over 60% of studies do not mention any communication protocols or standards. When standards are referenced (e.g., OpenADR and USEF), they are rarely integrated into the modelling framework. This lack of attention

to interoperability hinders replicability and scalability. For instance, Ref. [112] refers to these standards but does not integrate them into the modelling framework, remaining at a purely conceptual level. More advanced cases like [126] demonstrate the use of OpenADR in real-world pilots involving HVAC systems, consumption forecasting, congestion management, and DSO–aggregator coordination. This study stands out for implementing a modular and scalable platform based on open standards, even integrating blockchain for traceability and proposing a local market architecture compliant with European regulation. However, it stops short of testing synchronization across multiple local markets or simulating transactive energy environments. Similarly, Ref. [156] applies the USEF framework to explore DSO–aggregator interaction under varying levels of DER penetration. While it highlights the strategic role of aggregators and the potential of flexibility, it also reveals gaps in forecasting accuracy and the operational limits of storage assets. Flexibility is only triggered when congestion emerges, and many assumptions remain idealized. These cases illustrate that while some promising examples exist, interoperability is still addressed in fragmented way—rarely from a systems perspective that accounts for data latency, platform architecture, and cybersecurity. Without such integration, flexibility mechanisms lack the digital backbone required for scalable, secure, and replicable implementation.

Finally, most of the reviewed works cluster around TRL 6, corresponding to advanced prototypes, conceptual frameworks, and small pilots. For example, several studies on demand aggregation, EV-based services, and tariff-driven flexibility remain simulation-based or country-specific, often omitting interoperability and cost structures. By contrast, a smaller but significant subset reaches TRL 7, reporting large-scale field trials and commercial pilots. Notable examples include EcoGrid 2.0 in Denmark, which tested local flexibility with more than 800 households and demonstrated welfare gains during high-stress events; the InterFlex Dutch demonstrations, where layered congestion management mechanisms were validated in real networks; and the local capacity market pilots in the UK and Germany, showing that DSOs can defer reinforcement by contracting flexibility at the distribution level. Recent reviews of commercial flexibility products and platforms further illustrate this transition: Piclo Flex and Flexible Power operationalize the ENA standardized products across several European DSOs, enabling tenders with pay-as-bid procurement and settlement APIs; Enedis in France has launched national tenders for flexibility, albeit with limited participation; NODES operates cross-country with short-term and long-term products, supporting both DSO and TSO needs; and OMIE is developing an Iberian flexibility platform integrating day-ahead and intraday procurement into existing wholesale structures. These platforms represent TRLs 7–8 deployments, since they manage real assets, contracts, dispatch, and settlement, although challenges remain regarding liquidity, standardization, and interoperability. The distribution of benefits and risks is consistent across cases: DSOs accrue deferred reinforcement and reliability, aggregators bear coordination and baseline risks, and end-users capture modest financial gains but assume comfort or productivity trade-offs (e.g., greenhouse growers and commercial buildings). Taken together, these experiences confirm that flexibility markets are transitioning from TRL 6 to TRLs 7–8, but scalability to TRL 9 will depend on addressing regulatory fragmentation, interoperability gaps, and comprehensive cost–revenue frameworks that include ICT, onboarding, and transaction costs.

4.3. Thematic Gaps in the Literature

Beyond methodology, the review identifies several thematic gaps. One of the most pressing is the lack of integration between technical and economic layers. Few studies simultaneously model dispatch, market participation, revenue generation, and investment decisions. This separation limits the ability to evaluate the viability of flexibility business models and their long-term sustainability. In particular, the economic rationalization of ancillary services and flexibility products is often disconnected from their operational

justification. In [139], defining products purely on the basis of economic efficiency may lead to inefficient market signals and event double payments, especially in the absence of effective scarcity pricing mechanisms or when reserve procurement reflects conservative operator biases rather than stochastic equilibrium principles. These challenges suggest that restoring appropriate price volatility, expanding hedging instruments, and carefully designing products are essential for aligning operational uncertainty with investment incentives. Furthermore, this gap is amplified at the distribution level, where regulatory design remains in an experimental phase. As reported in [90], many jurisdictions are exploring different approaches for enabling flexibility procurement by DSOs, but there is still uncertainty about the cost-effectiveness and scalability of these initiatives. Issues such as tariff design, locational constraints, product standardization, and coordination with TSOs pose significant barriers. The lack of harmonized cost–benefit methodologies and the cautious attitude toward more dynamic network tariffs reflect a broader institutional and regulatory inertia that hampers the effective integration of flexibility across grid levels. As such, the economic viability of distributed flexibility is not only a matter of technical modelling, but also of institutional capability and policy coherence—aspects that are still insufficiently addressed in the literature.

A second gap concerns the treatment of end-users. Flexibility provision by households, SMEs, and energy communities is often discussed, but rarely modelled in detail. User preferences, comfort boundaries, and socio-economic barriers are underexplored. Most models assume passive responsiveness to price signals, which contradicts empirical evidence on demand response uptake. In [109], both preferences and socio-economic limits have been taken into account, but there is a lack of a wider range of articles that model them.

A third gap concerns institutional design and governance. While some studies mention the role of DSOs, regulators, or market operators, few examine in detail how coordination is implemented, how responsibilities are allocated, or how value is distributed. This omission limits the ability to assess the equity, fairness, or political feasibility of proposed flexibility mechanisms. For instance, Ref. [41] shows that conflicting incentives and duplicated payments can emerge when DSOs and TSOs seek similar flexibility services without proper coordination. In some cases, both DSOs and TSOs may end up paying for the same flexibility action, increasing overall system costs and undermining market efficiency. Additionally, certain congestion management mechanisms (such as peak or tiered tariffs) may be effective under specific conditions, but they can unintentionally reduce the aggregator's ability to participate in other markets. These reveal the need for more comprehensive governance frameworks that address the allocation of roles and the compatibility between different market layers. Without a clearer institutional architecture, flexibility markets become inefficient or politically unsustainable.

Finally, geographical coverage is uneven. Although the review includes studies from across Europe and beyond, the most detailed analyses are concentrated in a few countries (e.g., Germany, the Netherlands, UK, and Nordic countries). Contextual differences in regulation, market maturity, and user engagement are often ignored. There is a lack of comparative studies that evaluate how flexibility markets operate under different institutional or cultural settings.

4.4. Implications for Practice and Policy

The findings of this review have several implications for practitioners and policymakers. First, flexibility markets require more realistic, interoperable, and user-centred models. Relying on deterministic optimization with idealized agents is no longer sufficient. Future market designs must be stress-tested under uncertainty and take into account behavioural heterogeneity, information asymmetry, and transaction costs.

Second, market platforms should embed standardized protocols and data architectures. This is essential for ensuring interoperability, scalability, and cross-platform coordination. Projects such as InterFlex and OneNet point in the right direction, but their integration into academic modelling remains limited.

Third, tariff structures must evolve. Current models often rely on time-of-use pricing or simplified price signals. Real-world implementation will require layered incentives, combining availability-based payments, real-time signals, and dynamic access charges. Tariffs must also reflect locational value, grid constraints, and user equity considerations.

Fourth, the business case for flexibility must be clarified. Aggregators, DSOs, and prosumers need transparent mechanisms to recover costs, share value, and manage risk. This will require new approaches to cost allocation, benefit sharing, and regulatory alignment. A shared taxonomy of costs and revenue streams would improve comparability and support innovation. Moreover, the distribution of costs, benefits, and risks across DSOs, aggregators, and end-users has direct policy implications. DSOs require regulatory clarity to translate avoided CAPEX into recognized business cases and to justify ICT and compliance expenditures. Aggregators need frameworks that mitigate transaction costs, liquidity risks, and contractual complexity, especially for independent actors. End-users and prosumers, in turn, need fair remuneration schemes that offset comfort or productivity trade-offs and guarantee transparent participation. Without explicitly accounting for these actor-specific conditions, regulatory frameworks risk favouring incumbent players and undermining the scalability and fairness of flexibility markets.

Finally, policy frameworks must move beyond pilot projects and conceptual designs. Regulatory sandboxes have generated valuable insights, but the next step is to institutionalize flexibility mechanisms within electricity market design. This includes clear roles for aggregators, performance-based remuneration schemes, and integration into existing balancing and congestion management procedures.

4.5. Future Research Directions and Priorities

Based on the findings of this scoping review, we identify six research priorities. These priorities are not isolated but mutually reinforcing. Together, they aim to address the fragmentation, modelling limitations, and gaps in real-world applicability revealed throughout the literature.

1. **Integration of uncertainty in modelling frameworks**: While several studies recognize the stochastic nature of flexibility provision, uncertainty is often abstracted away or addressed through simplified sensitivity analyses. Future work should advance the use of stochastic optimization, scenario-based modelling, and probabilistic simulation techniques to reflect real-world conditions such as renewable variability, price volatility, and user behaviour. As demonstrated in Section 3.3.5, only a minority of studies incorporate robust scenario generation or risk-adjusted planning. This limits the capacity of current models to support investment decisions and market design under high-renewables and decentralized scenarios.
2. **Behavioural and socio-economic modelling of end-users**: Many studies assume passive or price-responsive behaviour, overlooking the heterogeneity of preferences, routines, and barriers that affect user participation. The literature underrepresents aspects such as comfort boundaries, rebound effects, and behavioural inertia. Future research should incorporate agent-based simulations, behavioural economics, and co-creation methods to capture the dynamic interaction between incentives and actual user responses. This is particularly relevant in low-voltage grids and energy communities, where social acceptance and perceived fairness can make or break flexibility mechanisms.

3. **Realistic cost structures and economic viability**: A key gap lies in the simplification of cost models, which often include only activation costs while ignoring transaction costs, ICT investments, user onboarding, coordination, and platform maintenance. As shown in Section 3.6.4, cost realism is especially poor in early-stage models (TRLs 1–3), limiting their use for scalability assessment. Future research must adopt more granular and comprehensive cost typologies, possibly aligned with techno-economic assessment (TEA) and total cost of ownership (TCO) frameworks. Exploring cost-efficiency trade-offs across flexibility types and deployment models (e.g., centralized vs. distributed) would be particularly valuable.
4. **Interoperability, standardization, and platform architecture**: Despite the centrality of digital infrastructure, interoperability is addressed in less than 40% of the reviewed studies (Section 3.3.6). This hinders the replicability and integration of flexibility platforms across jurisdictions. Future research should investigate open standards, layered architectures, and interface protocols, such as USEF, OpenADR, and CIM, not only from a technical perspective, but also from a governance and business model perspective. Platform design should be evaluated not only for performance, but also for data ownership, user trust, and regulatory alignment.
5. **Equity, risk-sharing, and institutional feasibility**: As discussed in Sections 3.6 and 4.3, the distribution of costs, benefits, and control remains largely unexplored. Future studies should analyze how flexibility mechanisms impact different user groups, especially vulnerable consumers, SMEs, and non-participating actors. Mechanisms for risk-sharing, fair remuneration, and revenue stacking across DSOs, TSOs, and aggregators need to be designed and evaluated, considering both efficiency and fairness. This also includes assessing institutional arrangements, such as role allocation, accountability, and dispute resolution in multi-actor flexibility schemes.
6. **Empirical validation, experimentation, and international comparison**: Only a small fraction of the reviewed studies rely on real-world data, pilot results, or cross-country comparisons. Model assumptions are often insufficiently validated, leading to a mismatch between simulated performance and observed dynamics. There is a need for greater emphasis on learning from demonstration projects, regulatory sandboxes, and real-world trials—especially for evaluating market design, user response, and platform operation. Furthermore, comparative studies between countries or regions can uncover contextual dependencies and transferability limits, helping to design flexibility mechanisms that are both scalable and locally adapted.
7. **Enhancing load restoration strategies through cross-sector flexibility.** Recent developments suggest promising avenues in coordinating the flexibility of buildings and electric buses during restoration scenarios. Leveraging thermal inertia and the spatiotemporal mobility of electric vehicles could significantly enhance grid resilience. Future studies should investigate fair allocation mechanisms, integrate sustainability metrics, and assess the societal impacts of prolonged outages, particularly in the context of decentralized energy transportation networks.
8. **Integrating cooperative game-theoretic approaches and multi-agent coordination.** Emerging research highlights the potential of cooperative strategies based on asymmetric negotiation to optimize interactions among heterogeneous agents—such as renewable generators, storage systems, and building loads. These approaches enable fair profit allocation, preserve agent privacy, and improve solving efficiency through advanced distributed algorithms. Exploring such models may provide more realistic, privacy-preserving, and computationally scalable coordination mechanisms for future flexibility markets.

Together, these directions form a coherent agenda to move flexibility market research from a fragmented and technology-driven space toward a more integrated, robust, and socially grounded science–policy interface.

5. Conclusions

In summary, this review provides a comprehensive and structured mapping of how energy flexibility markets are conceptualized, modelled, and analyzed across the academic literature. By integrating actor-oriented frameworks and business modelling tools, the study exposes persistent gaps in areas such as interoperability, market coordination, and value capture mechanisms.

While substantial progress has been made in defining market architectures, modelling aggregator behaviour, and developing flexibility metrics, the treatment of critical dimensions—particularly economic, behavioural, and institutional aspects—remains fragmented. Cost considerations, which are essential for the viability and scalability of flexibility mechanisms, are inconsistently addressed. ICT investments, coordination overheads, and user compensation are often overlooked or treated superficially, and most modelling approaches rely on simplified, deterministic assumptions that fail to capture the complexity and uncertainty real-world energy systems.

Despite these limitations, emerging trends indicate a shift toward more integrated and operationally grounded models. There is growing attention directed to economic realism, risk distribution, and the contextual adaptation of frameworks to local flexibility markets. However, key challenges remain, particularly regarding the standardization of evaluation metrics, the design of multi-actor coordination mechanisms, and the empirical validation of business models that can effectively align technical feasibility with market incentives and regulatory constraints.

Looking ahead, advancing flexibility markets will require greater interdisciplinarity to develop transparent, modular, and data-driven tools. These tools should be capable of handling the heterogeneity of resources and actors, the temporal and spatial variability of demand and supply, and the governance trade-offs between centralization and decentralization.

Ultimately, the insights provided in this review can inform the design of next-generation flexibility markets, guide regulatory experimentation, and support the co-creation of adaptative governance frameworks that are both technically robust and societally legitimate.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en18195213/s1, Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist [198].

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Data Availability Statement: The dataset supporting the findings of this study is openly available in Zenodo at https://doi.org/10.5281/zenodo.15572885. It includes the full data extraction matrix used in the systematic review, along with a "Read Me" sheet detailing the content and structure of each tab. The dataset is provided to ensure transparency and reproducibility, and to support further research in the field of flexibility markets.

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Abbreviations

The following abbreviations are used in this manuscript:

ABM	Agent-Based Models
ADMM	Alternating Direction Method of Multipliers
BMC	Business Model Canvas
BSUoS	Balancing Services Use-of-System
CBA	Cost–Benefit Analysis
CIM	Common Information Model
DA	Day-ahead
DER	Distributed Energy Resources
DSO	Distribution System Operator
DUoS	Distribution Use-of-System
EV	Electric Vehicle
FMP	Flexibility Market Platform
FSP	Flexibility Service Provider
HEMS	Home Energy Management System
IoT	Internet of Things
IRRE	Insufficient Ramping Resource Expectation
LFM	Local Flexibility Market
LMP	Locational Marginal Pricing
LORP	Lack of Ramp Probability
LP	Linear Programming
MCP	Market Clearing Price
MILP	Mixed Integer Linear Programming
NPV	Net Present Value
OPF	Optimal Power Flow
OpenADR	Open Automated Demand Response
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews
P2P	Peer-to-Peer
QoS	Quality of Service
RES	Renewable Energy Sources
RT	Real-time
SCR	System Capability Ramp
SGAM	Smart Grid Architecture Model
SO	System Operator
TEAM	Technological, Economic, Actor and Market
ToU	Time-of-Use
TNUoS	Transmission Network Use-of-System
TRL	Technology Readiness Level
TSO	Transmission System Operator
USEF	Universal Smart Energy Framework
VPP	Virtual Power Plant
WoS	Web of Science

Appendix A

Table A1. Data extraction table.

Section	Column	Type	Description
General Data	Authors	Free text	List of all authors
	Title	Free text	Full paper title
	Year	Numeric	Year of publication
	Source title	Free text	Journal or conference proceedings
	DOI	Text	Digital Object Identifier (if available)
Objective and research question	Paper type	Choice	Review, Modelling, Empirical, Experimental
	Research question	Free text	What problem or research gap does the paper aim to address?
	Future work	Free text	Open questions or future work proposed by the authors
Flexibility	Definition	Free text	How is flexibility defined?
	Type	Choice	Explicit/Implicit
	Metrics	Free text	e.g., ramp rate, time response
Modelling assumptions	Rationality	Choice	Perfect/Bounded/Not specified
	Information symmetry	Boolean	Do all agents share the same information?
	Grid constraints	Free text	Are physical grid limits included?
	Tariffs	Free text	e.g., Static, dynamic, ToU, real-time tariffs.
	Algorithms	Free text	e.g., LP, MILP, AI, heuristic, agent-based, game theory.
	Technology Readiness Level	Numeric	TRL 1 (basic research) to TRL 9 (commercial deployment)
Interoperability	Standard used	Free text	e.g., OpenADR, IEC 61850, Modbus, OpenFMB.
Market participants and enablers	Aggregation level	Choice	Household, SME, Industry, Community, Aggregator, VPP
	Time scale addressed	Free text	e.g., Intra-day, Day-ahead, Weekly, Seasonal.
	Agent	Choice	Consumer, Prosumer, Aggregator, DSO, TSO, Grid Operator
	Flexibility role	Choice	Provider, Requester, Coordinator, Enabler
	Coordination paradigms	Choice	Centralized, Decentralized, Hierarchical, Peer-to-peer
	Level of coordination	Choice	Local, Regional, System-wide; Distributed vs. Global
	Strategic behaviour	Free text	Any modelling of gaming, bidding strategy, selfish behaviour
Business Model	Value proposition	Free text	What value or benefit is provided, and to whom?
	Customer segments	Free text	e.g., Individuals, DSOs, communities, etc.
	Channel	Free text	e.g., Platforms, aggregators, etc.
	Cost structure	Free text	e.g., CAPEX, OPEX, cost- vs. value-driven.
	Revenue streams	Free text	Fixed/dynamic pricing, incentives, savings
Results, conclusions and recommendations	Main findings	Free text	What are the key insights, results or takeaways from the study?
	Limitations	Free text	What are the limitations, caveats or uncertainties?
	Benefits and risks	Free text	How are risks/rewards distributed among actors?
	Rating	Choice	High/Medium/Low
	Notes	Free text	Any extra comments

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